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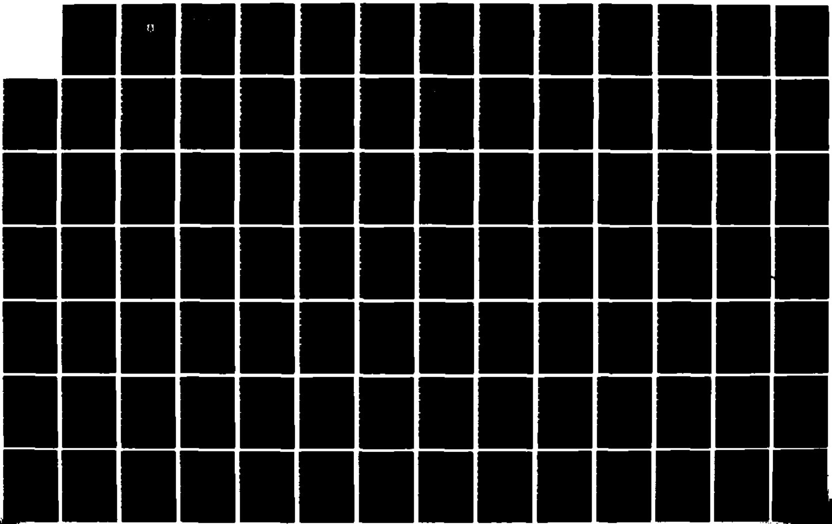

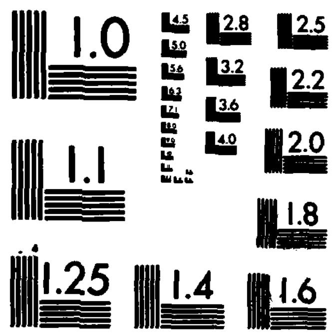

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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

PROBLEMS OF TECHNICAL ELECTRODYNAMICS
(Selected Articles)

FOREIGN TECHNOLOGY DIVISION

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UNEDITED MACHINE TRANSLATION

FTD-ID(RS)T-1430-83 11 April 1984

MICROFICHE NR: FTD-84-C-000367

PROBLEMS OF TECHNICAL ELECTRODYNAMICS (Selected Articles)

English pages: 101

Source: Problemy Tekhnicheskoy Elektrodinamiki, Nr. 38, 1972, pp. 1-13; 52-57; 77-93

Country of origin: USSR
This document is a machine translation.
Requester: FTD/TQTD
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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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PROBLEMS OF TECHNICAL ELECTRODYNAMICS.

In the collector/collection are connected the articles, in which the results of the theoretical and experimental studies of electromagnetic and thermal processes in the powerful/thick turbogenerators, asynchronous and inductor alternators, the linear induction machines and the transformers, the electrical machines with the windings from the superconductive and pure metals are represented.

The methods of calculation of electromagnetic fields, parameters and heating of generators and induction machines of different types are presented, are given the results of experimental investigations on the physical models, and also the full-scale tests of powerful/thick turbogenerators.

It is designed for the scientific and technical-engineering workers, who carry out questions of electrical engineering, graduate students and the students of the corresponding specialties.

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PROBLEMS OF INVESTIGATIONS AND INCREASE IN THE RELIABILITY OF POWERFUL TURBOGENERATORS IN THE 70'S.

I. M. Postnikov.

(Institute of electrodynamics of AS UkSSR).

L. Ya. Stanislavskiy.

NII of plant "Elektrotyazhmash"].

Volume and rate of the production of powerful/thick turbogenerators in our country continues to grow/rise in accordance with the marked state plan/layout. Into the forthcoming decade must be introduced in the operation of new turbogenerators not less than 150 mln. kW. This task can be solved only with a continuous increase in the power of turbogenerators in one (to 2000 MW and above), and also the continuous improvement of their technology and increase in the reliability in the operation.

Primary meaning in the forthcoming decade they will have

turbogenerators of the contemporary, but considerably improved construction/design. At the end of this period it is possible to expect introductions to the field testing of cryoturbogenerators and MHD generators.

Should be noted the basic problems, which require intense scientific investigations and technological developments.

First of all, is necessary the creation of the whole or composite/compound reliable in mechanical sense forgings of rotors with a weight of 250 t and it is more and rotor binding bands. These forgings must be intended for manufacturing the turbogenerators for the atomic stations with a power of 2000 MW and it is above.

Is required the creation of highly reliable insulation/isolation to the stress/voltage 25 kV and it is above, the capable of resisting increasing mechanical stresses from the electrodynamic forces. These forces can reach 10 t on the rod and act with a frequency of 100 per/s. It is necessary to develop the reliable system of fastening the stator winding in the active and end connections.

The problem of cooling the coils of stator-rotor unit, active steel and some structural/design parts remains unresolved, in spite of considerable achievements in this region in recent years. Water

cooling is most effective and it is sufficient to reliable ones. However, transition/transfer in the turbogenerators to one type of cooling would be faulty. It is necessary to investigate other cooling systems (improved hydrogen, freon, oil). Transition/transfer to the cryogenic cooling requires considerable preliminary investigations for the reliability and the efficiency/cost-effectiveness. The creation of the improved cooling systems requires the development of such calculation methods, which would include complex study of heat withdrawal, temperature field and local heat sources both with that being steady and during the transient modes/conditions. The investigation of heating with the deviations of run from the nominal (cyclic ones load, asymmetry, etc.), is important task.

Serious problem remains the development of the fail-safe design of the end zone of turbogenerators in connection with an increase in their power (extreme bundles of stator, fittings/landings of binding bands on the barrel/budy of rotor, pressure plate, etc. of part). Numerous propositions in this region have a number of shortcomings and need calculated and experimental check. Extreme bundles undergo considerable temperature and mechanical stresses and is decreased the reliability of turbogenerator.

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The methods of electromagnetic, thermal and mechanical calculations of turbogenerators in many respects need refinement during the development of the new constructions/designs of turbogenerators.all of the increasing power. The calculations of additional losses in coil and steel, incremental losses in tail pieces, the calculation of the parameters taking into account operating conditions, the optimization of geometric relationships/ratios, an increase in the use of materials, mechanical problems vibration need the use/application of contemporary mathematical methods and the testing on the physical models and full-scale samples with the use of the created at the Kharkov plant "Elektrotyazhmash" of test bench with the load turbogenerator of the type TTH-1000 (1 mln. kW, 24 kV, 3000 r/min).

A question about the possibility of increasing the transfer reactivity and reducing the o.k.z. [expansion unknown, possibly "short-circuit ratio"] with further increase in the power of turbogenerator in one due to the improvement and the new methods of increasing the stability of multiple operation is special problem.

The problem of noncontact excitation requires the acceleration of the investigations of the created pilot models of brushless exciters for the turbogenerators with a power of 200 and 300 thousand kW. It is simultaneously necessary to work on improvement of contact

system.

Especially should be noted the need for the creation of the large/coarse model turbogenerators, on which it would be possible to conduct experimental research of the reliability of different structural/design units of machine, systems of cooling, excitation, and so forth. Expenditures for creation and study of such model turbogenerators will be paid due to increase of the reliability of the produced machines and shortening of the period of their finishing. These machines include the already manufactured generator of the type TГH-1000. Simultaneously should be developed the studies of turbogenerators under operating conditions, stored and studied the obtained information. It is necessary to place the problem of developing of the new methods of control and observation of the working units for the timely development/detection and the preventions of emergencies, to refine the permissible modes/conditions.

Increase of reliability - basic problem of power engineering of the nearest future. This relates to all its elements/cells (generators, turbine, transformers, network/grid and system). The expansion of this problem requires investigations both in each branch and comprehensive investigations, since many questions are interlocked. It is necessary to create the appropriate organization

of this work with the collaboration of the institutes of AS UkSSR, branch institutes and leading plants.

PROBLEMS OF THE CREATION OF TURBOGENERATORS WITH WINDINGS FROM SUPERCONDUCTORS AND PURE METALS.

G. G. Schastlivyy, G. M. Fedorenko, V. P. Kuyevd, V. P. Kuchinskiy.

(Institute of electrodynamics of AS UkSSR).

An increase in the unit power of units and power stations as a whole is the characteristic feature of the development of turbogenerator construction. With a rapid increase in the power systems this depends on the need of reducing/descending in the capital expenditures and periods of building, decrease of expenditures for operation and increase of efficiency of installations.

In the industrially developed countries the unit power of turbogenerators is doubled after every 7-10 years. The units with a unit power of 800-1200 MW at present are already manufactured or are made.

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At this rate of development it is possible to assume that in the near

future unit plant capacity to be increased to 2-5 mln. kW. Isogonal magnification in the unit power must occur in essence due to further intensification of electromagnetic loads, since an increase in the dimensions is limited by maximum mechanical stresses and possibilities of transportation. In this case an increase of electromagnetic loads in conventionally configured turbogenerators leads to a considerable increase in the losses.

New possibilities for the progress in large/coarse electric machine building open/disclose study of superconductors and pure metals during the cryogenic cooling. The use/application of these materials makes it possible to increase current density in the windings by 1-2 orders, and induction in the clearance - 5-10 times without the essential losses of electric power.

The general/common/total technical and economic substantiation of the use/application of superconductors and pure metals in the electrical machines is stated sufficiently fully in the Soviet and foreign literature [1, 4, 10, etc.], where the basic special features/peculiarities and the tasks, connected with the creation of similar machines, are noted also. These special features/peculiarities and tasks are determined, mainly, by use of ultralow temperatures (4-20° K) for cooling of coils and by a considerable increase in the electromagnetic loads. The

use/application of a deep cooling proves to be economically more advantageous in comparison with the common when

$$\frac{P_x+N_x}{P_N}=\frac{P_x}{P_N}\left(1+\frac{T_0-T}{T\eta}\right)<1,$$

where P_x - losses, which appear at a low temperature; N_x - expenditure of the power of cooling installation; P_N - coil loss with the normal cooling; T/T_0-T - efficiency of Carnot cycle; η - relative efficiency of real cooling installation.

Dependence $\frac{P_x+N_x}{P_N}=f(T)$, found for different metals [10], makes it possible to reveal/detect the strongly expressed minimum, which for copper Cu,,,,, and aluminum Al,,,,, is located in the temperature range of liquefying hydrogen or neon. In this case to temperature $\frac{P_x+N_x}{P_N}=0{,}2\div0{,}25$, which makes it possible to increase the power of machine two times. In the examination of this dependence by heat flow from without they disregard, since with respect to the coil losses at a temperature of 20° K it does not play the significant role. In the case of using the superconductors of coil loss, which are located in the magnetostatic field, they are absent and the expenditures of the power of cooling installation occur only for coating of heat flow from without.

Since the winding from the superconductors must be located at a temperature, close to 4.2° K, this heat flow considerably grows/rises, and expenditures for branch/removal 1 W from the

temperature level 4.2° K become by an order more than expenditures for branch/removal 1 W from the volume, which is located at 20° K. All this substantially affects the economic effectiveness of the use/application of superconductors in the windings of electrical machines. However, at present a question about the use/application of superconductors in the fixed windings of direct current can be considered solved. Organization IRD (Great Britain) manufactured disk type unipolar superconductive engine with a nominal power of P=2400 kW; n=200 r/min; I=5800 A; U=430 V; f=6.45 Wb [11]. The superconductive electric motor with 200 r/min can be created to the nominal power to 40000 kW, while for the common electrical machines of direct current a maximally attainable power at this rotational speed is approximately/exemplarily 10000 kW. Engine with the superconductive excitation winding weighs 30 t. The engine of the same power of normal design has dimensions three times more and weigh 300 t.

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Hard superconductors [illegible] type Nb_3Sn or NbTi in the alternating magnetic field have the considerable losses, proportional to frequency. Therefore the use/application of superconductors in the turbogenerators is limited only to excitation winding.

Creation of the optimum construction/design of turbogenerator with the rotating superconductive excitation winding - extremely complicated question, which requires deep theoretical developments and careful experimental investigations. The creation of the rotating cryostat, which ensures minimum heat flow into the low-temperature part with the necessary mechanical strength and rigidity of system is basic task in this case.

In work [3] the construction/design is proposed, which is one of the possible prototypes of the construction/design of the rotor of powerful/thick turbogenerators with the superconductive excitation winding. On the base of this construction/design in NII of plant "Elektrotyazhmash" is developed and at present is made the model of the turbogenerator with a design capacity of 200 kW.

The carrying part of the rotor (Fig. 1) of this model is nonmagnetic hollow cylinder 6, connected at the ends with the pins/journals of halyard 9 through thermo-insulating sections 3, which are selected from uniform strength condition with the solid shaft. The material, from which thermo-insulating sections are made, the maximum possible relationship/ratio σ/λ provides, where σ - limit of mechanical strength, and λ - coefficient of thermal conductivity. Construction/design provides for also use for cooling these sections of the refrigerant vaporized in the low-temperature region. All this

provides minimum heat flow on the thermo-insulating sections. The external surface of cylinder is encircled by vacuum jacket 5, which serves as the effective thermal insulation, which is independent of the action of centrifugal forces. Within the vacuum jacket heat shield 4, made from material with the high thermal conductivity and which uses for the protection of low-temperature volume from the heat flow, caused by radiation/emission, is located. Outer casing of 1 vacuum jacket is made from the material with the high electrical conductivity and serves simultaneously as the electromagnetic shield, which shields the superconductive excitation winding by 7 from the alternating magnetic fields, caused by the asymmetry of load and by the highest harmonic armature reactions. The losses, which separate in the shield, are abstracted/removed by the helium gas, which comes out from the rotor through clearance 2. From the ends/faces low-temperature volume, with the excitation winding arranged/located in it, is shielded from the heat flow by vacuum plugs 10. The superconductive excitation winding is attached on framework/body 8.

The published results of the investigations, conducted abroad and connected with the use of superconductors in the rotating excitation winding of turbogenerators, confirm the correctness of the constructive solutions accepted. In works [6-8] it is imparted about the conducting of investigations in the experimental machine with the rotating hyperconductive (SP) excitation winding. It is double-pole

generator of 3600 r/min, designed on 80 kVA, 450 A.

The basic goal of investigation was the proof of the possibility of the construction of the rotating cryostat with the placed in it SP excitation winding. Experiments with the short circuit were carried out during the operational conditions, the mode/conditions no-load condition and with the low voltage. Investigations showed that the rotating SP excitation winding can successfully work in the synchronous generator.

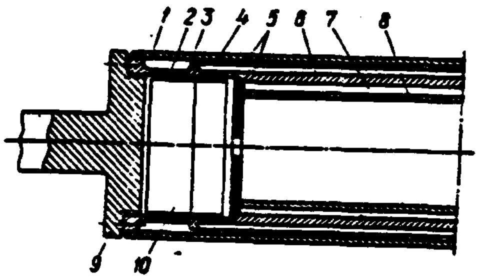

Fig. 1.

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The results of the tests of the generator, designed on 80 kVA, served as basis for the creation of the design of cryoturbogenerator with a power of 1000 MW [8, 9]. The average value of current density in SP excitation winding is accepted by 124 A/mm² with the maximum induction 5.5 T.

Diagrammatic representation of rotor (Fig. 2) makes it possible to speak about the essential similarity of this construction/design with that proposed in [3]. In both cases the rotor is nonmagnetic cylinder 3, connected with the center shafts 8 by thermo-insulating sections 1. Low-temperature volume with the located in it SP excitation winding 5 is cooled by liquid helium and is encompassed by vacuum jacket 4. Both constructions/designs have thermoelectric shield 2, which rotates together with the rotor. However, there are

some differences.

In the construction/design of rotor according to work [3] electromagnetic and heat shields are located on the different temperature levels: the first at a normal temperature, the second at a temperature of 77° K. According to work [9] the functions of these shields are united and joint shield is located at a temperature of 20° K. Vacuum jacket around rotor [9] is made with the vacuum seal on shaft 6, since its upper jacket/case/housing 7 is fixed. Taking into account the considerable diameter of driven shaft, which transmits the power of 1000 MW, the speed of rotation - 3600 r/min and the vacuum necessary for the effective thermal insulation (not less than 10^{-8} mm Hg), accomplishing this sealing/packing/compaction is problematic. In the construction/design according to [3] vacuum-tight volume is rotated together with the rotor, in this case high vacuum is provided by the welded joint of electromagnetic shield and carrying cylinder and by the use/application of an adsorbent. The design of tail pieces of the rotor also is somewhat excellent, since in the construction/design accordingly [8] for cooling the thermo-insulating sections is not provided for complete use of the helium gas coming-out from the cryostat and it is considered that the basic thermal inflows will be absorbed by electrothermal shield.

From the given comparison it is possible to mark the general

view of the rotating cryostat with the superconductive excitation winding placed in it. At the same time the execution of its separate units can be very diverse. In this case special attention should be given the mechanical calculation of the versions of rotor in question.

Besides the minimization of heat flow into the rotating cryostat complex problem is the guarantee of thermal stability of the winding during a deep cooling, which is determining, in the final analysis, the overload capacity of electrical cryo-machine. Windings with the superconductivity can be cooled by liquid or gaseous helium. Most effective is considered cooling as the liquid boiling gas, when heat of vaporization is utilized. A difference in the temperatures of winding and cooling medium in this case is very low, if does not occur excess of critical heat flux per unit of surface.

Table gives critical heat fluxes with nucleate boiling and the temperature differentials between cooled surface and cryogenic liquid in the large volume at a pressure 1 atm(tech) [10].

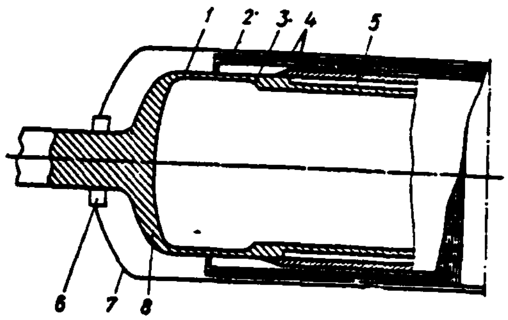

Fig. 2.

(1) Криогенная жидкость	(2) Критический тепловой поток, вт/см²	(3) Перепад температуры, град
He	0,8	0,6
H_2	9,0	3,0
N_2	19,0	12,0

Key: (1). Cryogenic liquid. (2). Critical heat flux, t/cm². (3). Drop/jump in temperature, deg.

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The specific heat of superconductors at low temperatures becomes is very low. In connection with this the winding with the overloadings cannot accumulate heat, but as far as possible it loosens to its cooling medium. Although the heat-transfer coefficient of the boiling refrigerants is sufficiently great, this causes the low constant value of the heating time. Therefore with any load the temperature of winding immediately is established/installed, so that

the losses, which separate in the winding, and the heat, which enters from without, are located in the equilibrium with cold output of the cooling medium. Of the aforesaid it above follows that the thermostability of cooling the coils of cryo-machine is lower than machine with the normal cooling, and it is provided under condition

$$\frac{dq}{dT} > \frac{dP_z}{dT}.$$

If we cool the winding only by gas, then in the overloadings winding immediately is heated. Thus, as a result of the considerably smaller heat capacity of gas winding with the gas cooling has smaller overload capacity than during the cooling by the liquid boiling gas. Increases in the thermal stability and, consequently, also the overload capacity of winding it is possible to attain due to an increase of the volume of refrigerant in the winding space, reaching/achievement of a maximally possible heat-transfer coefficient and increase in effective output of cooling installation. Studies of heat emissions in the cryogenic liquids are scarce, carried out in essence on the body surface of the simplest form (plane, cylinder) and require careful developments.

In connection with the insufficient dielectric properties of helium important significance has a creation of electrical insulation, which could successfully work in the conditions of cryogenic cooling and large mechanical loads.

The winding of the stator of cryoturbogenerators can be made both with the common and with the cryogenic cooling. The presence of the superconductive excitation winding makes it possible to obtain working induction on the order of 4-5 T, which gives the possibility to construct/design the stator of gearless with the armature winding arranged/located in the clearance. The values of the efforts/forces, which affect on the stator winding, it grows/rises approximately/exemplarily proportional to the square of the linear load of stator. In the turbogenerators with the direct cooling of coils the amplitude value of the effort/force, which affects on the groove part of the rod, reaches 10 N, while in the emergency modes - 700 N. On the end connections of the stator winding act smaller efforts/forces than to the groove. Nevertheless in the powerful/thick turbogenerators during the short circuits the tangential component of effort/force, which affects on the end connections, attains 200 N [5]. The mentioned efforts/forces act in the turbogenerators with the linear load 1600-2200 A/cm. In the cryoturbogenerators with a power of 1500-2000 MW linear load grows/rises 2-2.5 times, the electrodynamic efforts/forces, which affect on the winding, will be raised in this case 4-6 times in the normal modes of work. All this makes a question of the stability of the windings of cryoturbogenerators to the action of electrodynamic efforts/forces

especially urgent.

The absence of magnetic circuits in the working zone of machine, a considerable increase in the linear loads is connected with the essential effort/force of stray fields, which in turn leads to an increase in the losses in the conducting structural elements/cells. This causes the need for the careful investigation of the methods of decreasing the stray fields and losses caused by them, and also research of the optimum cooling systems of the structural elements/cells of cryoturbogenerators.

In view of an abrupt change in the electrical parameters of the windings of cryoturbogenerators and flywheel moment of rotor are necessary careful studies of the transient modes of an operation, and also questions of the static and dynamic stability of machines.

Thus, it is possible to draw the conclusion that creation in the near future of cryoturbogenerators - completely real task.

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However, a question of the creation of the optimum construction/design of turbogenerator with the superconductive excitation winding extremely complicated and requires deep

theoretical developments and careful experimental investigations.

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PROBLEM OF A FULL-SCALE HIGH-POWER MODEL GENERATOR.

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Heavy electric machine construction has pronounced tendency toward a constant increase in the unit powers of machines, especially turbogenerators, with a simultaneous reduction/descent in the weight per the unit of power.

The creation of the turbogenerators of large power in the building of thermal power stations makes it possible to get great economy according to the specific expenditures for the installed kilowatt, efficiency of installation, the expenditures for the operation of installation. Is decreased the specific cost/value of the installed by the station equipment, and also the specific consumption of reactive metal, which is evident from the table, in which the specific consumption of the metal of turbogenerator 100 MW is accepted as one.

The very important advantage of thermal power plants is a comparatively rapid input/introduction into the system of large

powers, approximately/exemplarily 2-3 years after the beginning of building. At present installed capacity of turbogenerators in the foremost industrial countries comprises to 80-85% of total installed capacity of power stations.

(1) Мощность генератора, *Мвт*	(2) Удельный расход меди, *кг/мва*	(3) Удельный расход стали, *кг/мва*	(4) Общий удельный вес
100	1	1	1
200	0,9	0.49	0,66
300	0,86	0,48	0,63
500	0,6	0,4	0,44
800	0,465	0,328	0,381
1200	0,398	0,312	0,315

Key: (1). Power of generator, MW. (2). Specific consumption of copper, kg/mVA. (3). Specific consumption of steel, kg/mVA. (4). Total specific gravity/weight.

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The successes in the development of new methods and cooling systems of the active elements/cells of machine make it possible to virtually solve the problems of the maximum heating of the elements/cells of machine in the normal mode for the powers of order 1000 MW and more. However, high specific utilization of materials in the large/coarse turbogenerators leads to an unavoidable increase in the ratio of the linear load AS to the induction in clearance $B\delta$, since the power of machine with the prescribed/assigned dimensions is proportional to product $ASB\delta$, and the possibility of increase $B\delta$ is very limited due to the conditions of saturating the ferromagnetic elements/cells of machine. For example, upon transfer from the power of 500 MW to 800 MW, in spite of an increase in the diameter of rotor

from 1125 to 1200 mm, it was necessary to increase AS with 1975 A/cm to 2300 A/cm [4]. Increase AS leads to an increase of the current densities in the windings of stator-rotor unit, additional losses in the end part of the stator, an increase in the specific efforts/forces in the frontal and groove parts of the stator winding.

An increase of the unit power of turbogenerator with the increased linear load is possible first of all due to an essential improvement in the cooling systems and reduction/descent in some components of losses. However, an increase of unit power causes the increased requirements for the reliability of generator, which causes the need for comprehensive investigation. Orientation to the methods of analytical study without the widely set experiment is insufficient and cannot ensure full-valued results during the solution of problems for the adjustment of the versions of the new constructions/designs, new solutions. Experimentation with the working machines of large power proves to be not only difficult, but sometimes even virtually impossible. The occurring emergencies with different powerful/thick units are, on one hand, the direct consequence of the imperfection of the methods of analytical calculation of contemporary powerful/thick machines, and on the other - by the consequence of insufficient experimental study in view of the absence of experimental base, which could give valuable results and recommendations for further designing of the electrical machines of large power. The methods of calculation

of electrical machines, as is known, rest on the results of the studies of their electromagnetic fields. In the electrical machines electromagnetic fields are so complicated which for their successful study is required to draw all known methods of study.

The analytical method of study is one of the methods; however, it is based on a whole series of the assumptions, which make it possible to simplify task. The calculation procedures, based on these assumptions, give the possibility to obtain satisfactory results with the light electromagnetic loads and for the machines with the weakly expressed nonlinearity of media. For the powerful/thick turbogenerators in many instances the necessary precision/accuracy is reached due to the introduction of the correcting empirical coefficients, suitable for the specific level of loads.

Satisfactory results in the study of electromagnetic fields in the electrical machines it is possible to achieve during the combination of analytical method with the physical simulation. Actually physical simulation replaces experiment in nature, which is especially valuable for the large/coarse machines. It gives the possibility to investigate the phenomena, which occur in the places, unattainable for the observation in machine-original. The method of physical simulation makes it possible to investigate field in the machine without the assumptions of analytical theory, taking into

account nonlinearity, for anisotropy and by the presence of complex-shape structural/design parts. In IED of AS UkSSR with the aid of the physical model the whole complex of the studies of electromagnetic field in the end zone of powerful/thick turbogenerators [2] is conducted. The fact that the model is to a considerable extent similar to original, is a special feature/peculiarity of this form of simulation and identical physical quantities in the model and the original differ virtually only to the value of dimensionless scale coefficient.

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Between the model and the original there are solid mathematical relationships/ratios [1, 2], which make it possible to recount the results, obtained on the model, for the original.

The laws of the simulation of electromagnetic processes escape/ensue from the equations of Maxwell, which for quasistationary fields take the identical form for the model and the original:

$$\mathrm{rot}\, H = \gamma E, \qquad (1)$$

$$\mathrm{rot}\, E = -\frac{\partial B}{\partial t}. \qquad (2)$$

Analyzing equations (1) (2), we find the characteristic criterion of similarity for quasistationary fields with the constant magnetic permeability, which links magnetic permeability μ, specific

conductivity σ, time t and linear dimensions l:

$$\frac{l^2}{t}\mu\sigma = \text{idem}. \qquad (3)$$

During the simulation of quasistationary fields the scales of the magnetic field strength m_H, linear dimensions m_l, specific conductivity m_σ and magnetic permeability m_μ can be selected arbitrarily. In the case of patternmaking geometrically as a whole of the similar to a machine-original and with the use/application of the same materials, in the model and in a machine-original unambiguously are assigned the scales for magnetic permeability and specific conductivity: $m_\mu = 1; m_\sigma = 1$.

From equation (3) it follows that during patternmaking with the reduced linear dimensions in comparison with the original it is necessary to increase the frequency of the source of the excitation of field so that the relationship/ratio

$$m_t = m_l^2. \qquad (4)$$

would be fulfilled.

This means that for the creation of the rotating physical model, reduced in comparison with the original to $1/m_l$ times, will be required an increase in the speed of rotation of the rotor of model in the relationship/ratio:

$$n_м = m_l^2 n_0, \qquad (5)$$

where $n_м$ - speed of rotation of the rotor of model; m_l - scale

factor of linear dimensions; n_0 - speed of rotation of the rotor of a machine-original.

Hence it follows that the creation of the rotating physical model of the reduced sizes/dimensions during the simulation of the bipolar machines of ultimate capacity (turbogenerators) is limited by permissible mechanical stresses. For the simulation of these machines are suitable the static models, which do not contain the rotating parts, in connection with which of limitation on mechanical stresses they drop off. However, static model is inferior to that rotating in that sense, that, in the first place, in it can be satisfied the conditions of the similarity of electromagnetic field either in the region of stator or in the region of rotor [3], in the second place, on the static model it is difficult to conduct research, connected with testing of cooling systems, especially rotor, and also the investigation of the phenomena in the contact zone. If model is manufactured from the same materials, that also the original and, therefore, $m_\sigma = 1$, scale for contact electrical conductivity is not equal to one [3]:

$$m_{\sigma_k} = m_l^{-1}, \qquad (6)$$

where m_{σ_k} - scale factor of contact electrical conductivity.

In the model with the reduced sizes/dimensions contact conductivity must be increased $1/m_l$ once. This it is possible to

achieve either by an increase in the pressure between mating surfaces or by a use/application of the thin conducting layers of these surfaces with material with the high electrical conductivity, or by an increase in the frequency of the treatment of mating surfaces.

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Entire enumerated creates the series/row of difficulties with the work on static scale model.

As is known, an increase in the unit power of turbogenerator with the constant/invariable dimensions is possible due to an essential improvement in the cooling systems and reduction/descent in some losses, which can be realized during further improvement of the construction/design of tail pieces and use/application of completely new cooling systems, which will require comprehensive testing and investigations. For solving these questions it is necessary to fulfill the overall volume of experimental investigations and to accumulate experience, which cannot thus far be ensured by static scale models. Taking into account the known fact that with the increase of the electromagnetic loads of turbogenerators heating structural/design parts and butting zones by vortex/eddy and circulation currents becomes increasingly more dangerous, seizing all new and frequently unexpected zones, it is expedient to create the

special model generator with a power of 500-300 MW with the linear load at the level of the turbogenerator with a power of 1200 MW, which will ensure the solution of the following problems.

1. Testing the new technical solutions of constructing/designing tail piece of the turbogenerator of the large power (order 1200-1600 mW), which ensure a reduction/descent in the losses and heating of the stray fields of the elements of the construction/design of end zones in different operating conditions.

2. Reliability test under the conditions, close to the operational ones, the series/row of the basic units of tail pieces of the turbogenerator, which work in the stray fields, including pressure/clamping devices and extreme bundles of the core of the stator of different forms of sealings/packings/compactions and joints of different parts, oiled sealings/packings/compactions, current supplies, water-supplies, binding bands, end wedges and attenuators of rotor.

3. Further study of the characteristics of magnetic field in tail piece of the turbogenerator in the presence of different means of defense of basic units from the stray fields, the investigation of circulation currents, intensity of heat withdrawal and motion of the cooling media in tail pieces, and also testing new cooling systems,

including of speeds, temperatures, the pressures of the gaseous and liquid cooling media for the purpose of the refinement of the methods of calculation and substantiation of new solutions.

The institute of the electrodynamics of AS UkSSR developed the design of the model turbogenerator with a power of 429 mW, which is designed taking into account the familiar dimensions of the barrel/budy of rotor (D_2=1120 mm) and corresponding binding bands with the linear load AS, equal to turbogenerator 1200 mW.

Model is turbogenerator with the transverse dimensions, which approach turbogenerators of the type ТГВ-800 (ТГН-1000), with the reduced length for decreasing of power and consumption of materials up to the smallest possible limits. The length of active region/core is determined by the possibility of the execution of the transposition of the elementary conductors of the stator winding. The linear load of stator is the basic parameter of load, which are determining the intensity of stray fields in tail piece. Model is designed for the linear load 2700 A/cm with the continuous operation and on momentary duty with AS=3100-3200 A/cm. This will make it possible to simulate the magnetic field of turbogenerators to 1600 mW on the full-scale scale.

On the model the possibility of removal/distance and approaching

the panels (external end elements/cells of ducts) from the end connections is provided for, and also is structurally/constructionally provided for the possibility to test/experience several types of the cooling systems of model generator with insignificant re-equipping.

Projected/designed model of turbogenerator during the reconnection/recombination of the stator winding into one parallel branch permits using it as an operational version in a typical unit with a power of 300 mW. The model should be tested on the stand of plant in the mode/conditions short circuit and no-load condition, and also in the load mode/conditions with the load on the turbogenerator ТГН-1000.

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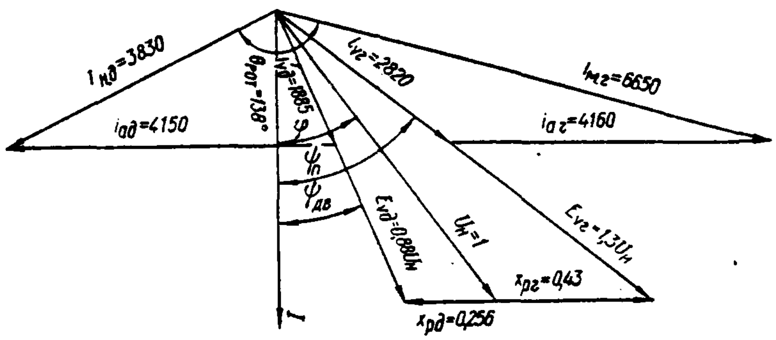
In this case the model generator with a power of 429 MW works in the mode/conditions of generator, as can be seen from the diagram of the pumpback (see figure), where $U_{\text{н}}$ - nominal voltage of the generator; $E_{0\text{г}}, E_{0\text{д}}$ - emf of model and load generators; $x_{p\text{г}}, x_{p\text{д}}$ - Potier's reactivity; $i_{\text{п.г}}, i_{\text{п.д}}$ - the full current of the excitation of model and load generators in the load mode/conditions; $i_{a\text{г}}, i_{0\text{г}}, i_{a\text{д}}, i_{0\text{д}}$ - components of field current; $\theta_{\text{рот}}$ - angle of the mutual arrangement of the rotors of generators in the load mode/conditions; $\psi_{\text{г}}, \psi_{\text{дв}}, \varphi$ - angles of the loads (g - it designates model generator, d - load generator ТГН-1000).

Has the capability of the creation of model generator with a power of 429 MW, which makes it possible to conduct comprehensive investigation and experimental production testing of new ideas and constructive solutions.



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TEMPERATURE FIELD OF THE CORE OF THE STATOR OF A TURBOGENERATOR WITH A POWER OF 200 MW.

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During tests of one of the turbogenerators with a power of 200 MW with the hydrogen cooling, preliminarily equipped with the necessary quantity of thermocouples, were carried out studies of the temperature distributions in the core of stator. Data finding about the temperature field of core is necessary for solving the number of questions during the design of the turbogenerators of large power,

including for the selection of the rational distribution of hydrogen according to air ducts of core, the account of its thermal strains during the development of the construction/design of the suspension of core in the housing, the evaluation/estimate of the displacement of core and winding relative to each other in the nonstationary systems, etc. Furthermore, the knowledge of the temperature distribution in the core makes it possible to improve the diagrams of plant thermo-control/thermo-checking. The theoretical solution of these questions is difficult in connection with the absence of the reliable data about the distribution of the values of heat-liberation value over the cross section of core (especially during the use/application of cold-rolled steel) and values of heat-transfer coefficients in air ducts. Values of the coefficients of thermal conductivity along and across the layers of blending very approximated.

The possibility exact solution of the enumerated problems makes it possible to considerably raise reliability and life of the operation of powerful/thick turbogenerators. Therefore data of the experiment, carried out directly under the load under operating conditions, are of considerable interest.

The results, given further, are obtained with the work of generator in the network/grid with the nominal load and the nominal

power factor. The generator ТГВ-200, on which the investigations were conducted, has following basic data: $P_{п} = 235$ MW, $P_{в} = 200$ MW, $I_{ст} = 8{,}63$ kA, $U_{ст}$ =15.74 kV, cos φ=0.85, the pressure of hydrogen in housing 4 atm(tech).

Cooling the coils of stator-rotor unit, core of stator, barrel/budy of rotor and structural/design assemblies and parts - hydrogen. Ventilation system - axial-radial with the gas supply into the core from the side of back, its output into the gap and further transportation to the side of turbine. In the stator winding the gas is supplied on the side of driver (high-pressure zone) and emerges on the side of turbine. In the rotor winding the gas is supplied from both ends/faces with the output in the middle part of the generator into the gap and further motion to the side of turbine. All this causes more severe temperature conditions for tail pieces on the side of turbine in comparison with the side of slip rings. The part of the cold gas through the multiplexing in the gap on the side of slip rings falls into air gap, in consequence of which cooling the barrel/budy of rotor and toothlike zone of extreme packets is intensified.

The core of stator is prepared from cold-rolled transformer steel with a thickness of 0.5 mm. Along the length the core is divided into 92 packets, each by the thickness of 50 mm, with the

radial ducts with a width of 5 mm.

For the best cooling and decreasing the losses from the magnetic fields of scattering on two extreme packets from the ends/faces of core they have a thickness of 36 mm each, and along the axis of the teeth of extreme packets gash-splines are carried out.

Before the tests, even in the process of manufacture of generator at the plant, into its core were established/installed about 500 thermocouples. Thermocouples were soldered directly to the surface of steel of segments (ten thermocouples - along the axis of tooth, and one - in the zone of the bottom of slot/groove). Segments were installed into the middle of packet. During this installation of thermocouples and segments the temperature field of packet is distorted minimally and simultaneously it is measured the temperature of packet in the plane of its maximum heating. In several segments for obtaining the more detailed data about heating of region the bottom of slot/groove - the foundation of tooth were established/installed supplementary thermocouples. It is necessary to note that the thermocouples in all packets are established/installed in one axial plane of tooth, surrounded by slots/grooves with the rods of one and the same phase. The investigations, carried out earlier, determined, that heating such teeth to 5-7% is more than the teeth, surrounded by slots/grooves with the rods of different phases.

Fig. 1 gives the graphs/curves of the distribution of temperature excess of toothlike zone and framework of packets along the length of core (numeral on diagram - number of packets). Is here shown the diagram of installation of thermocouples in the core and the separate segment, from which it is evident that is measured the temperature of each of five-six extreme packets and three packets, which are located opposite the zone of the yield of "hot" gas from the rotor winding. The curves of Fig. 1 attest to the fact that the temperature distribution along the length of core is sufficiently uniform. In the toothlike zone (thermocouples TП1, TП2, TП3) certain increase in the temperature on the side of turbine in comparison with the side of slip rings is observed. In the middle part of the core (packets 39-48) on heating of teeth (especially crown) has an effect the "hot" gas, which emerges from the rotor (temperature it is raised on 3-5 deg). However, with the work of generator in the modes/conditions with decrease in the consumption/production/generation of reactive power or its consumption even decrease in the temperature in the toothlike zone is possible, since the temperature of "hot", gas, which emerges from the rotor, will be considerably lower than in experiment in question.

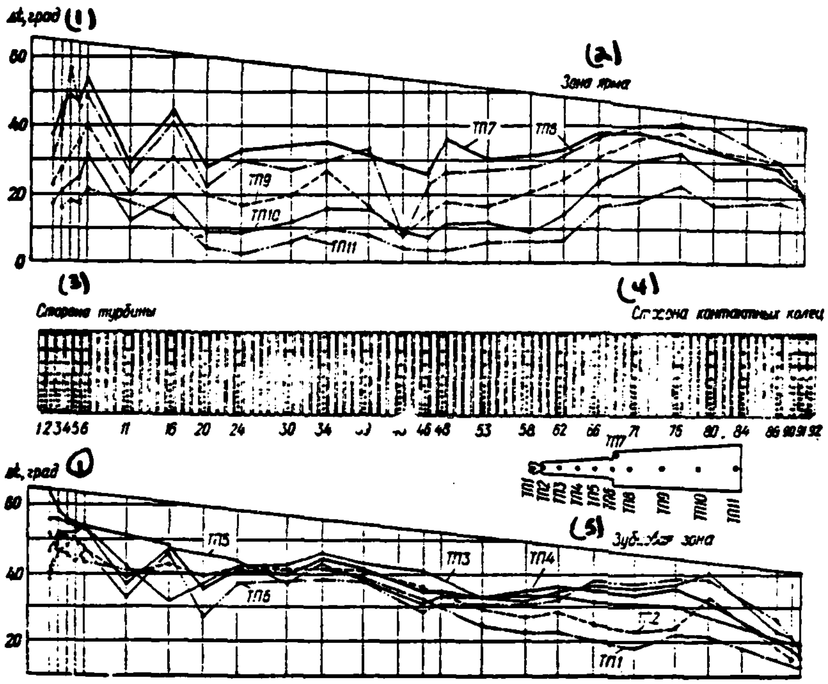

Fig. 1.

Key: (1). deg. (2). Zone of framework. (3). Side of turbine. (4). Side of slip rings. (5). Toothlike zone.

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For heating of the teeth of extreme packets on the side of slip rings, obviously, considerable effect exerts the "cold" gas, which falls into the gap through multiplexing of air gap. From Fig. 1 it is evident that into air ducts of extreme packets on the side of slip

rings (and especially into the gap/interval between the first extreme packet and the pressure plate/slab) the increased quantity of gas in comparison with other zones along the length of core is supplied. Thus, on the side of turbine in the section, which encompasses 5-6 extreme packets, heating packets is somewhat increased in comparison with the remaining part of the core. It is possible to consider that the gas flow through air ducts of these packets is somewhat lowered.

It should be noted that in the toothlike zone the difference of readings/indications in depth of tooth in each radial section is considerably less than in the region of back.

Fig. 2 gives the graphs/curves of the distribution of temperature excess in two extreme packets on the sides of turbine (packets 1 and 2) and slip rings (packets 91 and 92), also, for the comparison - in average/mean packet 46. In the diagram of the location of sensors, shown here it is apparent that in packets 1 and 92 segments are established/installed on the boundaries of the steps, into which extreme packets are divided. Gash-splines in the teeth of these packets are carried out only in three steps (segments along the axes I, II and III), and in the fourth they are absent (axis IV). The location of thermocouples in the segment is analogous with the location, shown in Fig. 1. Segments along the axis are established/installed in the third from the end/face layer of steel.

Are shaded the zones, in which readings/indications of all different thermocouples, established/installed in packets 1 and 92 without the separation into the steps, are placed.

The examination of the graphs/curves Fig. 2 testifies about the fact that on the side of slip rings temperature excess comprises not more than 25 deg. On the side of turbine (packets 1 and 2), where the conditions of cooling the packets heavier, heating are considerably above, and the temperature distribution carries sharply nonuniform character. The greatest temperature differential from the back to tooth tip is 55 deg. Noticeably sharp increase in heating the zone of the bottom of slot/groove, foundation of tooth and its crown. In this case it is characteristic that if the greatest heating in the zone of the bottom of slot/groove is measured directly near the surface of the end/face of core (axis I), then in the zone of foundation and tooth tip the maximum temperature is measured at the depth of 8-10 mm from the end/face of core (axis II). This is explained by the screening effect of the nonmagnetic conducting pressure/clamping finger/pin. Magnetic flux flows about the it and enters into tooth from the side of slot/groove at certain distance from the end/face.

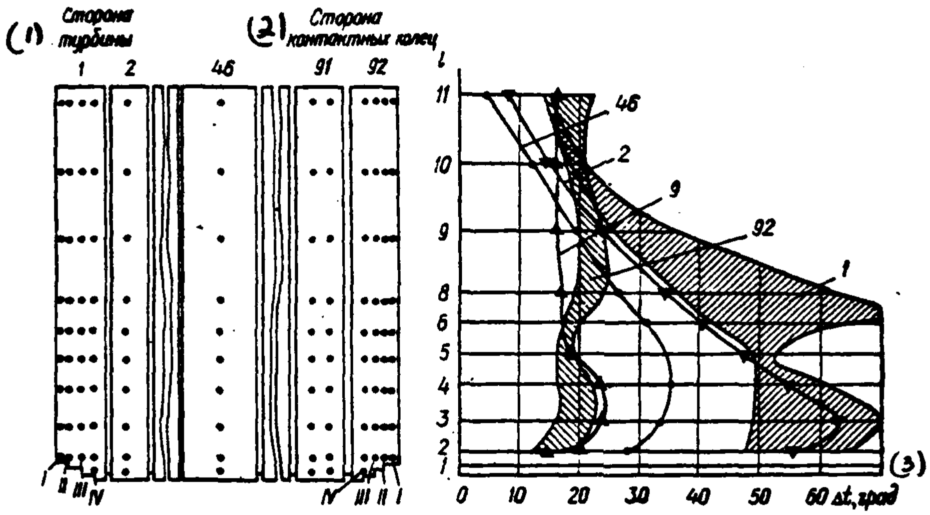

Fig. 2.

Key: (1). Side of turbine. (2). Side of slip rings. (3). deg.

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Near the crown in connection with the gradation of the extreme packet of condition for the input of magnetic flux it is direct from the end/face more favorable. In the middle part of the extreme packet (axis III) heating toothlike zone is considerably below, moreover maximum is measured near the zone of crown. In the same zone along the axis IV is measured certain increase in the temperature, which is explained by the fact that in the fourth step there is no spline-gash in the tooth. It is interesting to compare the temperature

distribution in packets 2 and 46. In proportion to the motion of the cooling gas (from the back to the teeth and further to the gap) the temperature is raised, but in the toothlike zone in packet 2 this increase is continued virtually to the level of crown, and in packet 46 change of the temperature is small. Near the gap, where gas intensely circulates, in these packets even decrease in the temperature to 15-20% in comparison with its maximum value is observed.

On the side of slip rings the character of the temperature distribution is analogous; however, the value of temperature excess Δt in the toothlike zone of packets 91, 92 is 2.5-2.8 times less than respectively in packets 1 and 2. It is interesting that in the zone of the framework of extreme packets on the side of slip rings the value Δt already is 1.5-2.0 times more. This, obviously, it is determined by certain preheating of gas during its transportation from the side of the turbine (are there arranged/located gas condensers) to the side of slip rings along the skin/sheathing and the cylinder, which encompasses core.

Fig. 3 gives data, in more detail characterizing distributions temperatures in the segment of the first extreme packets (segment with the gash), on the sides of turbine and slip rings. The distribution curves of the temperature were constructed for the

radial sections А, Б, В, Г, Д and tangential I, II, III, IV, V, VI, moreover designation for the side of slip rings - with the primes. Fig. 3a depicts the temperature distribution along the axes of slots/grooves А and Д, in Fig. 3b - over the radial sections Б, В, Г, in Fig. 3c - in the circle/circumference of core over the tangential sections. The diagram of the layout of thermocouples is here given. The graphs/curves Fig. 3 confirm conclusion, done in the examination of Fig. 2, and they show that the greatest heating of core near the end/face is characteristic for the zone the bottom of slot/groove the foundation of tooth.

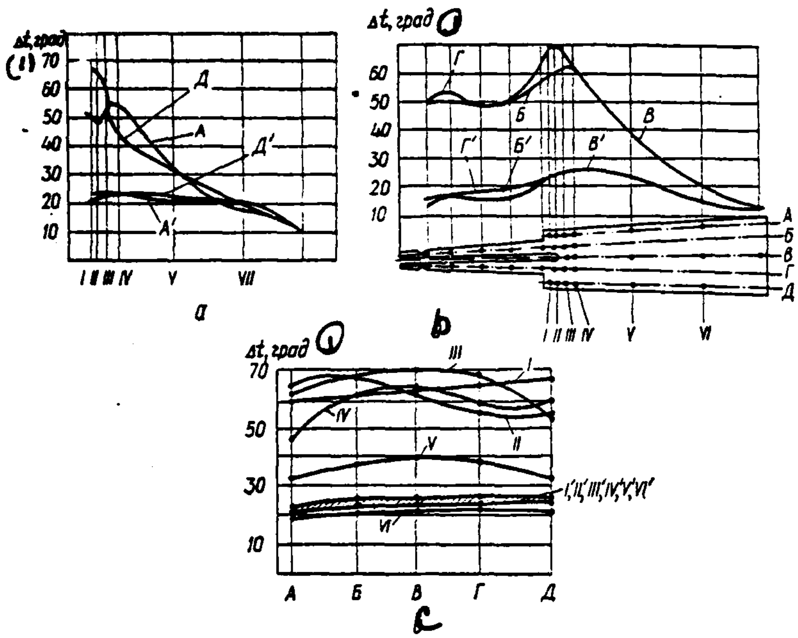

Fig. 3.

Key: (1). deg.

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Temperature sharply descends in proportion to removal/distance in the direction of back, for the pressure collar, which plays the role of screen.

On the basis of that presented it is possible to do following conclusions. The temperature distribution in the core, with exception

of extreme packets, is relatively uniform with certain increase in the temperature on the side of turbine. On the side slip rings certain decrease in the temperature is determined by the more intense cooling of toothlike zone by the "cold" gas, passing through multiplexing of gap.

For decreasing heating extreme packets on the side of turbine it is expedient to produce the redistribution of the gas flow through the separate sections with a considerable increase in the consumption through the first extreme section on the side of turbine, which is possible during the adjustment of diaphragms in the vent openings of the lower covering of core; in the newly produced generators a gash-spline along the axis of teeth to prolong to the side of back on 15-20 mm for the collar, that will lead to certain decrease in the losses in the zone of the foundation of teeth and bottom of slots/grooves, in the newly produced generators the width of two outer air ducts on the side of turbine to increase to 8-10 mm, as a result of which will increase the intensity of cooling two extreme packets.

EXPERIMENTAL STUDIES OF THE MAGNETIC FIELD IN THE END ZONE OF A TURBOGENERATOR WITH POWER OF 200 MW WITH CHANGE OF cos φ.

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During the complex tests of turbogenerator by a power of 200 MW were carried out the studies of the magnetic field of scattering in the end zone, including in the extreme packets of core. Test program provided for conducting several load modes/conditions with the constant active power and different power factors, including with the consumption of reactive power from the network/grid.

Basic data of generator and the diagram of ventilation are analogous described in work [1], but the tested generator, which has the water cooling of the coils of stator, has somewhat different construction/design of extreme packets. The first extreme packets

have a thickness on 31.5 mm, radial ducts have a width of 10 mm, but the teeth of extreme packets have not one gash-spline, but two (i.e. tooth it is divided into three parts and each it has its pressure finger/pin made of nonmagnetic steel). Tooth here is wider, since in this generator of 30 slots/grooves, but not 60 as in that described in work [1]. Slot/groove in the core of the stator of generator the less deep, i.e., inner diameter of pressure/clamping collar has smaller size/dimension.

During the production at factory the core of stator was equipped with sensors for induction measurement in accordance with specially developed methodology [2]. The extreme packets of core were especially thoroughly equipped.

Let us give some results of the study of the axial component of magnetic induction in the zone of extreme packets on the side of turbine. Fig. 1 shows the diagram of the layout of the sensors of induction in two extreme packets: in the first extreme packet the segments with the sensors are established/installed through 8 mm in accordance with the gradation of packet, moreover the first segment is located near the end/face of core; in the second packet the segments are established/installed in two sections, on the boundaries $^1/_3$ and $^2/_3$ the thickness of packet.

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The first three steps of extreme packet have gash-splines.

The graph/curve Fig. 1 shows the distribution of axial component of induction B_z in the radial direction in the nominal rating (cos φ=0.85), also, with cos φ=1.0. In the shaded zones readings/indications of all sensors are placed. curves make it possible to determine, that maximum values B_z are characteristic for the toothlike zone of extreme packet. In this case distribution B_z according to the thickness such, which is directly under pressure/clamping fingers/pins B_z is less by 15-20% than on the boundary of the first and second steps (at the depth of 8 mm). Further into the depth of core value B_z descends sufficiently sharply and already in third-fourth packet virtually it is absent.

In the toothlike zone at the level of the foundation of tooth value B_z almost is three times less than in the zone of crown; in the region of the back, shielded by the pressure/clamping collar, which works as screen, values B_z are lower by an order and more. With change cos φ from 0.85 (inductive load); to 1.0 fundamental change B_z it is measured in the zone of maximum values, i.e., near tooth tip.

Fig. 2 gives the data of change B_z in different zones of extreme packet from cos φ: curve 1 corresponds to tooth tip of extreme packet near the end/face of core, curves 2 and 3 - to middle this of tooth Ja of packet in end/face, curves 4 and 5 - to zone two slots/grooves. Curve 1 corresponds to the scale of values B_z to the left, rest - to the right. From Fig. 2 it is evident that greatest relative change B_z occurs in the zone of the bottom of slot/groove (curves 4 and 5).

Here induction grows/rises in the range of change cos φ from 0.85 (ind.) to 0.95 (cap.) by 25%. In the middle part of tooth B_z it grows/rises by 15-20%, while in the zone of crown - to 10%.

A change in temperature excess in two extreme packets in this range of change cos φ is virtually equal. In this case in the region of back, values B_z barely change.

Thus, with change cos φ in the modes/conditions to the consumption/production/generation of reactive power from consumption considerably varies the axial component of induction in the extreme packets. Maximum value B_z is characteristic for the zone near tooth tip, near the foundation of teeth B_z it already composes 0.3 this value, and in the region of back it is insignificant due to the pressure/clamping collar screening effects.

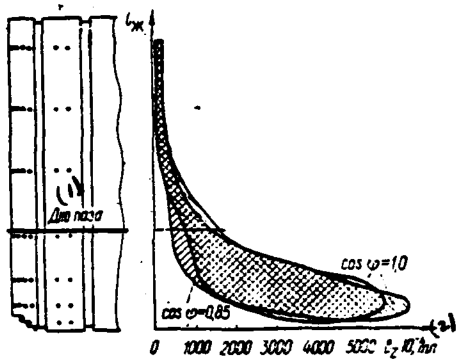

Fig. 1.

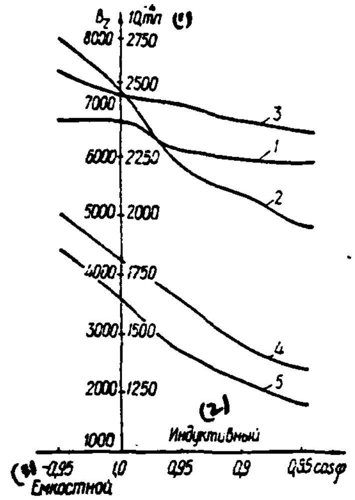

Fig. 2.

Fig. 1.

Key: (1). Bottom of slot/groove. (2). T.

Fig. 2.

Key: (1). T. (2). Inductive. (3). Capacitive.

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METHOD OF MEASUREMENT OF THE MAGNETIC FIELD ON THE SURFACE OF THE STRUCTURAL PARTS OF THE END ZONE OF POWERFUL TURBOGENERATORS.

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Complicated character and the sufficiently high intensity of magnetic field in the end zone of powerful/thick turbogenerators causes the need for the experimental investigations of its distribution on the surfaces of basic structural/design parts. In this case the necessity of the measurement of field on the surface of the elements of construction/design appears. The accuracy of measurement must be sufficient high, in particular for the tangential component of magnetic field strength H_τ on the surface of conductive body, which is the basic value, which characterizes the course of electromagnetic processes in the conductive bodies (determination of specific surface losses, complex skin drag, etc.). The fact that it substantially changes with the removal/distance from the surface of

part, is the special feature/peculiarity of distribution H_τ. Consequently, the accuracy of measurement H_τ is determined by distance from the axis of sensor to the surface being investigated. For achievement of larger accuracy it is possible to measure the field at several points at the different removal/distance from the surface of part, and then by extrapolation to determine the value of field on the surface.

For the measurement of the tangential component of magnetic field strength H_τ were utilized the flat/plane inductive-type pickups, which were established/installed in pairs directly on the surface of part in such a way that the axes of sensors would be directed mutually orthogonally at each measured point.

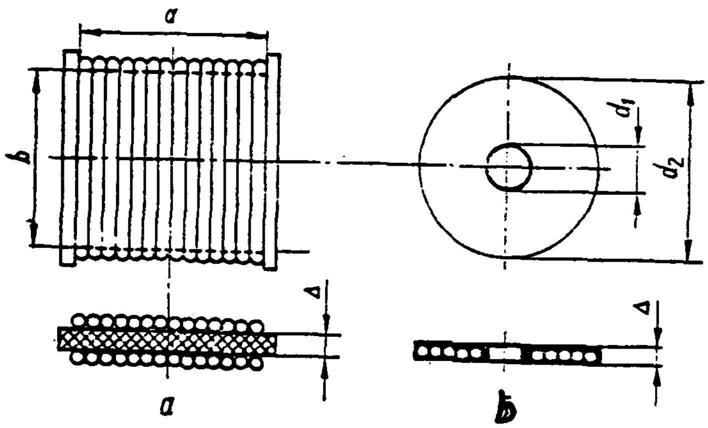

Fig. 1.

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Sensor is the coil, wound by the lead/duct of brand PETV with a diameter of 0.1 mm into four layers to the framework/body from the textolite plate with a thickness of Δ=0.5 mm, with a length of a=10 mm and with a width of b=10 mm (Fig. 1A). The overall thickness of sensor does not exceed 1.5 mm, which makes it possible to measure the tangential component of magnetic field strength H_τ virtually on the surface of part.

For the measurement of the normal to the surface component of magnetic field strength H_n the circular induction coils, wound by the lead/duct of brand ПЭВ-2 with a diameter of 0.07 mm in the form of flat/plane spiral, were applied, so that the thickness of sensors is

determined by the thickness of lead/duct and does not exceed 0.1 mm. during surface mounting of part the axis of sensor coincides with normal to the surface. Inner diameter of circular coils d_1=2 mm, outside diameter a_2=10 mm (Fig. 1b). For convenience in the installation on the even/plane and available surfaces of parts the sensors were installed in the textolite laths, which then were fastened to the surface of part with bolts from insulation. In the places, unattainable for the installation of laths, the sensors were established/installed independently.

The sensors described above had a series/row of technological errors during the production, which caused the need for their calibration in the uniform magnetic field employing the following procedure. Sensors were placed into the magnetic field of solenoid, and the effective values of emf, aimed in them, were measured by a selective vacuumtube voltmeter of the type B-6-4 and were duplicated/backed up/reinforced by a vacuumtube voltmeter of the type Ф-506. As is known, the effective value of emf, aimed in the coil, is determined by the expression

$$E = 4.44 f n B_{max} s \; [в], \qquad (1)$$

where f - frequency, Hz; n - number of turns of coil; B_{max} - maximum value of the induction of magnetic field, T; s - sectional area of the mean turn of coil, m^2.

Coefficient of 4.44 in formula (1) is valid for the sinusoidal form curved emf. For the sensors, mounted on the surface of the massive parts of the end zone of turbogenerator far from air gap, curved emf according to the data of harmonic analysis are virtually sinusoidal. Taking into account that $B_{max} = \mu_0 H_{max}$, we determine the maximum value of magnetic field strength:

$$H_{max} = CE\ [a/м], \qquad (2)$$

where C - constant of sensor,

$$C = \frac{1}{\mu_0 4.44 f n s}\ [a/м \cdot в]. \qquad (3)$$

After calibrating the constants of sensors for the measurement by normal and the tangential component of magnetic field had a spread with respect (to 2.1-2.4)·10³ A/m·V and (6.2-6.6)·10³ A/m·V. In the measurement of magnetic field on the surface of the parts of turbogenerators the constants of sensors were not neutralized, but they were taken individually for each sensor. Sensors of such type were established/installed on the surfaces of the structural/design parts of the end zone of a turbogenerator of the type TГB-300. Its basic data are the following: $P_н = 300$ MW, $U_{ст} = 20$ kV, $I_{ст} = 10{,}2$ kA, cos φ=0.85. Nonmagnetic pressure flange (Fig. 2) is made from the circular (1) and cylindrical (2) parts, connected by stiffening ribs (3).

Generator was tested at the Tripol'skaya GRES [State Regional Electric Power Plant] in experiment symmetrical three-phase short

circuit when $I_{ст} = I_{ном}$. The results of the investigations, carried out earlier [1], testify that the intensity of magnetic field on the surfaces of structural/design parts is determined in essence by the value of armature current. Fig. 2 gives the distribution curves of the components of magnetic field on the surface of the pressure/clamping flange of generator from the side of turbine according to three mutually orthogonal axes: to n, x and to y.

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Axis n coincides with external normal to the surface of the part being investigated, and x and y axes lie/rest at the plane, the tangent to the surface of part at the point in question (y axis is normal the plane of drawing and is directed toward us, while x axis it is arranged/located so that axes n, x and y form the right-handed coordinate system). In this case it is accepted that H_x, H_y and H_n - effective values of tangential and normal components of magnetic field strength on the surface of part. By measured values H_x and H_y at each point of surface was determined resulting tangential component of magnetic field strength:

$$H_\tau = \sqrt{H_x^2 + H_y^2}\ [a/м]. \quad (4)$$

The same figure shows the distribution of resulting tangential component of magnetic field strength on the surface of pressure/clamping flange. Obtained data testify about the

concentration of magnetic field in two zones of the pressure/clamping flange: in the circular part of the flange about the output/yield of the stator winding from the slots/grooves and in the cylindrical part near the end connections of the winding. This confirm the distribution curves of temperature excesses of flange Δt above the ambient temperature (see Fig. 2). Certain increase of the field in upper half of the circular part of the flange is explained by the effect of ferromagnetic parts (tie prisms, nut).

On the surfaces of pressure/clamping flange, turned to the end connections of the stator winding, the average/mean effective values of resulting tangential component of magnetic field strength were counted For the circular and cylindrical parts of the flange these values are equal to with respect $94 \cdot 10^2$ to A/m and $200 \cdot 10^2$ A/m, and according to the data of work [1] - $116 \cdot 10^2$ A/m and $235 \cdot 10^2$ A/m. Thus, difference composes approximately/exemplarily 15-20%, which during the.calculation of losses composes error 30-40%. This disagreement is explained by the fact that applied earlier for the study of magnetic field sensors [1] were large circular volumetric coils, whose axes were located from the surface being investigated on 12-18 mm. Consequently, these sensors can be applied for the study of magnetic field in air around the end connections of the windings and one ought not to apply for measuring the field on the surface of parts.

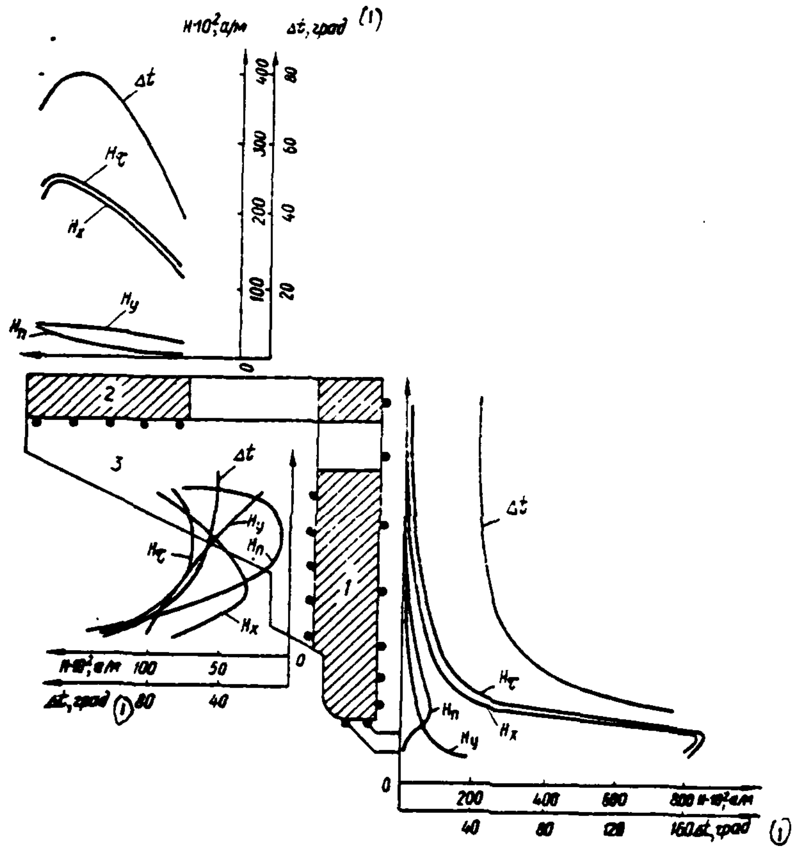

Fig. 2.

Key: (1). deg.

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Thus, is developed the new construction/design of inductive-type pickups for measuring the magnetic field in immediate proximity of

the surface of the parts being investigated, which made it possible to investigate the distribution of magnetic field on the surface of the pressure/clamping flange of the turbogenerator with a power of 300 thousand kW of the type ТГВ-300.

Obtained experimental data can be used for refining of those existing and development of the new analytical methods of calculation of magnetic field and losses in the structural/design parts of turbogenerators, and also during the design of new powerful/thick turbogenerators.

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PROBLEMS OF CALCULATION AND DETERMINATION OF THE PARAMETERS OF THE EQUIVALENT THERMAL CIRCUITS OF WATER-FILLED ELECTRIC MOTORS.

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In different regions of national economy electric-pump units with the immersible electric motors as the drive increasingly more widely are applied. In connection with this high value has a reliability and a life of the units indicated. Operational experience shows that the majority of the emergencies of immersion electric pumps occurs as a result of the breakdown of insulation/isolation of the winding of the electric motor, caused by unsatisfactory thermal conditions. This position to a considerable degree is explained by insufficient attention to the thermal processes, which occur in the immersible electric motors. the methods of calculation and analysis of thermal processes, developed for induction motors of the general-purpose use/application, can give only approximate results with their use/application to immersion electric motors, the immersible liquid-filled electric motors on the design concept, the intensity and the location of internal heat sources, in cooling conditions differ significantly from the electric motors of

general-purpose use.

The results of the experimental studies of temperature fields [5] and their analysis show that for the thermal designs of the immersiblé water-filled electric motors is applicable the principle of superposition, in this case the thermophysical characteristics of bodies, the volumetric heat capacity and the coefficient of thermal conductivity, the intensity of the volumetrically distributed sources of heat, condition of heat exchange on the boundaries of bodies can be accepted by constants for the temperature range in question. If necessary the refinement of the thermal design is achieved by the method of consecutive corrections.

The equations of heat balance for n of the mutually-heated bodies, taking into account the two-stage theory of heating closed induction motors [3], let us write in the matrix form:

$$\|\Lambda_{ij}\|_1^n \cdot \|\vartheta_i\|_1^n = \|p_i\|_1^n, \qquad (1)$$

where $\|\Lambda_{ij}\|$ - symmetrical matrix/die of the n order of heat conductivity; $\|\vartheta_i\|$ and $\|p_i\|$ - columnar matrices/dies of the temperatures and losses in the separate elements/cells of the n order.

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Hence we find

$$\|\vartheta_i\|_1^n = \|r_{ji}\|_1^n \cdot \|p_i\|_1^n, \qquad (2)$$

where $\|r_{ij}\|_1^n$ -- matrix/die, reverse/inverse with respect to matrix/die $\|\Lambda_{ij}\|_1^n$.

Expression (2) is actually the solution of system of equations (1). Virtually it is reduced to the determination of the reciprocal matrix of heat conductivity. Coefficients r_{ij} of the system of relationships/ratios (2) can be calculated according to the known formula of Cramer

$$r_{ji} = \frac{M_{ij}}{\Delta}, \qquad (3)$$

where Δ - determinant of matrix/die $\|\Lambda_{ij}\|_1^n$; M_{ij} - the cofactor of equivalent component Λ_{ij}, the definition, which is obtained by deleting in Δ the row and the column that intersect on element/cell Λ_{ij}, furnished with factor $(-1)^{i+j}$.

Should be focused attention on the fact that element/cell r_{ji}, which is located on the intersection of row j and column i in reciprocal matrix $\|r_{ji}\|^n$, corresponds in the conductance matrix to subdeterminant M_{ij}, which relates to element/cell Δ_{ij}, which is located on the intersection of row i and column j. During the calculation and the analysis it is convenient to represent solution (2) with the help of the integral thermal parameters in the following form:

$$\Theta_i = \frac{\sum\limits_{j=1;\,j\neq i}^{n} k_{ij}p_j + p_i}{\Lambda_i} + \frac{\sum\limits_{i=1}^{n} p_i}{\Lambda_\kappa}, \qquad (4)$$

where Λ_i - integral heat conductivity of body i to the housing; Λ_κ - the heat conductivity of housing to the environment; k_{ij} - influence coefficient of the losses of body j heating body i.

On the one hand, the knowledge of the integral thermal parameters of the type k_i simplifies complicated equivalent thermal circuit, while on the other, with known Λ_i it makes it possible by the method of simple recalculations to obtain overheating the elements/cells of machine interesting us in different operating modes.

In the general case the integral thermal parameters can be determined from (1):

$$k_{ij} = [-1]^{(i+j)} \cdot \frac{M_{ji}}{M_{ii}}, \qquad (5)$$

$$\Lambda_i = \Lambda_{ii} - \sum_{j=1;\,j\neq i}^{n} k_{ij}\Lambda_{ij}, \qquad (6)$$

where $\Lambda_{ii} = \sum\limits_{i=1}^{n} \Lambda_{in}$ - integral heat conductivity of node/unit i of equivalent diagram.

On the basis of the generalization of data of theoretical analysis and results of the experimental study of the temperature fields of electric motors of the type PEDV the refined equivalent

thermal circuit (ETS) of the determination of heating the basic elements/cells of the immersible water-filled electric motor without the forced internal circulation of the cooling fluid (Fig. 1) is proposed. This diagram makes it possible to also fully compare the correctness of the calculations of heat conductivity and distribution of losses with the calculated and experimentally obtained gradients of temperature. So as for the machines of general-purpose use/application [3], is here used the principle of symmetrization relative to the axial axis of machine, which makes it possible virtually two times to decrease a number of bodies of equivalent thermal circuit without a reduction in the accuracy of calculation. In the represented winding diagram of stator is divided on two tele-p groove part (8) and end connections (9). Heating rubbing surfaces of bearings with a sufficient accuracy is determined by the temperature of their surrounding water (node/unit 10).

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Water in the zones of the near-frontal spaces of winding has virtually identical temperature, i.e., it is experimentally established/installed, that in this region the essential gradients of temperature are absent. This bears out the fact that in spite of the absence of the organized internal circulation of liquid, the rotation of rotor ensures its sufficiently intense mixing within the engine.

This makes it possible to isolate water within the engine into one body and to consider that the heat transfer in it is realized by convection. In work [2] is determined the critical speed of flow, upon the reaching/achievement by which it is expedient to consider the thermal conductivity of liquid. It is shown that the critical speed is relatively small.

The package of stator is three sources: yoke p_{j1}, teeth p_{z1}, p_{z2}. The distribution of specific losses in steel of the package of stator was obtained by thermometric method. Fig. 2 gives the results of the experimental investigation of losses in package of stator of an engine of the type ПЭДВ-65-270 with the nominal stress/voltage. In the yoke the losses are distributed virtually evenly, what cannot be said about teeth. The ratio of maximum specific losses in the teeth to the averages can be accepted by the equal to 2-3. Nodes/units 1, of 2 and 3 equivalent thermal circuits (see Fig. 1) give the possibility to fix the radial gradients of the temperature of package.

The experimental studies of temperature fields make it possible to draw the conclusion that in axial direction of rotor are not observed the dangerous gradients of the temperature and in the practical calculations it is possible to be bounded to the representation of the rotor winding by one body 6. The housing of

stator is three bodies: 12 - housing in the zone of the package of stator, 13 - housing in the zone of end connections of the stator winding, 14 - housing in the zone of axial thrust bearing.

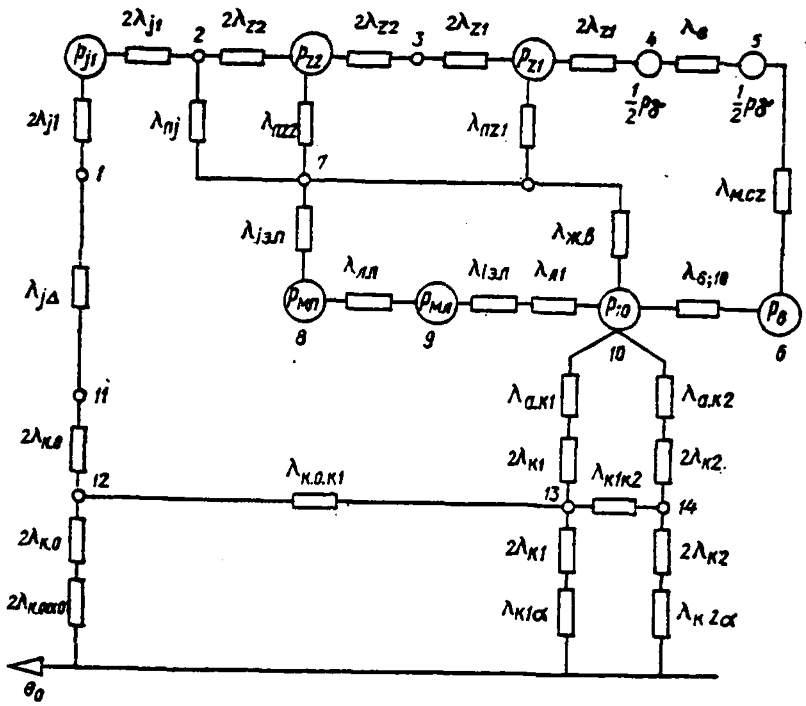

Fig. 1.

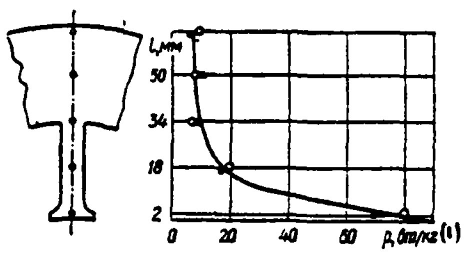

Fig. 2. Key: (1). W/kg.

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Mechanical losses have exceptionally important value for determining of efficiency and calculation of heating. With an increase in the single power liquid-filled electric motors the

relative value of mechanical losses in their total sum increases. This is evident from table 1. losses in the clearance between the rotor and the stator compose basic part of the mechanical losses. As is shown calculated analysis, losses in the clearance of a liquid-filled electric motor it is most expedient to determine by the method, described in work [1]. Losses in the clearance of the liquid-filled electric motor on the design diagram are represented as surface by two sources 4 and 5 [5].

Losses to friction of faces of rotor against the liquid as a result of the large ratio of the length of rotor to its diameter (see Table 1) compose negligible value. However, losses to bearing friction comprise in those water-filled to valence diagram they are seemed node/unit 10.

Reliable determination of heat conductivity - necessary condition for the successful use/application of the proposed calculation method. The heat conductivity, represented in Fig. 1, it is possible to divide into three basic groups: 1) the heat conductivity of walls or rods of the simplest geometry with the internal heat releases or without them; 2) heat conductivity from the cooled surfaces to the cooling medium in accordance with the boundary third-order condition and the equation of heat emission; 3) the heat conductivity of filled windings $\Lambda_{(эп)}$, $\Lambda_{(из)}$ [1].

The first group of heat conductivity is determined by the formula

$$\Lambda_{ij} = \lambda_{ij}\frac{S_{ij}}{\delta_{ij}}\cdot\xi_{\theta}, \qquad (7)$$

where λ_{ij} - specific heat conductivity of wall by thickness δ and with area S; ξ_θ - calculated coefficient, which considers the character of temperature field. With a linear change in temperature $\xi_\theta = 1$, with parabolic $\xi_\theta = 3$.

According to this formula it is possible to determine the heat conductivity of teeth and yoke $\Lambda_{z1}, \Lambda_{z2}, \Lambda_{j1}$, the clearance between the package of stator and housing $\Lambda_{j\Delta}$, slot liner Λ_{ni}, Λ_{nz1}, Λ_{nz2}, of housing along axis $\Lambda_{к.с}$, $\Lambda_{к.о.кi}$, $\Lambda_{кi}$, $\Lambda_{к2}$, the axial conductivity of winding $\Lambda_{в.л}$. The calculation of these heat conductivity [3] in no way differs from the calculation of the corresponding conductivities of closed induction motors of the general-purpose use/application.

The determination of the heat conductivity of second group [2] presents essential difficulties in the thermal design of the water-filled electric motors. Heat conductivity from the housing to cooling medium $\underbrace{\quad}_{}^{(\Lambda_{к.оα}, \Lambda_{к1α}, \Lambda_{к2α})}$ can be approximately determined with the use of the known criterial dependence for the annular channel.

Table 1.

(1) Мощность электродвигателя, квт	(2) Отношение длины ротора к его диаметру, отн. ед.	(3) Механические потери, квт	(4) Механические потери от общей суммы, %
4,5	3.83	0,184	16,2
16	5.46	0,510	18,3
65	4.43	3,790	38,3
90	5.48	5,420	40,7
500	9,23	35,0	49,2

Note. The synchronous speed of 3000 r/min.

Key: (1). Power of electric motor, kW. (2). Ratio of the length of rotor to its diameter, rel. un. (3). Mechanical losses, kW. (4). Mechanical losses from the total sum, %.

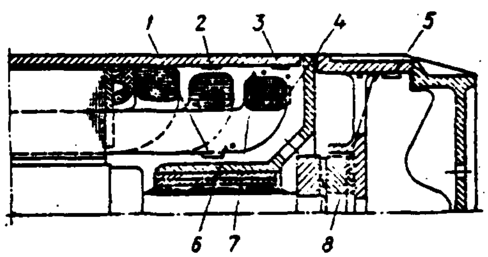

Fig. 3.

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The determination of heat-transfer coefficients in the zone of end connections of the windings and housing $\Lambda_{л1}$, $\Lambda_{в.к1}$, $\Lambda_{в.к2}$, presents the greatest difficulty since data according to the heat-transfer coefficients in the zone of windings and panels of the liquid-filled electric motors in the Soviet and foreign literature are absent. In

connection with this the experimental investigation of heat-transfer coefficients with the help of special sensors [4] was carried out. As the subject of investigation is used the engine of the type ПЭДВ-65-270, in tail piece of which the sensors of heat emission 1-5, velocity transducers 6-8 and sensors for measuring the temperature (Fig. 3) were established/installed. Engine was filled with water (Θ=30-50°C) or transformer oil (Θ=40-60°C). The control of the speed of rotation of engine was realized from the auxiliary machine of direct current.

The results of investigations are generalized in the form of dependences.

With the filling of engine with transformer oil heat-transfer coefficient for the end connections of the windings of the stator

$$\alpha_{\text{лч}} = 77(1 + 0{,}417v^{0{,}754}), \qquad 0 \leqslant v \leqslant 15; \tag{8}$$

for the housing of stator in the zone of end connections of the winding

$$\alpha_{\text{в.к}} = 77(1 + 0{,}432v^{0{,}454}), \qquad 0 \leqslant v \leqslant 15; \tag{9}$$

for the pedestal body

$$\alpha_{\text{к.п}} = 110(1 + 0.358v), \qquad 0 \leqslant v \leqslant 5, \tag{10}$$

$$\alpha_{\text{к.п}} = 110(1 + 0{,}05v^{0{,}402}), \qquad 5 \leqslant v \leqslant 15. \tag{11}$$

With the filling of engine with industrial water for the end connections of the winding of the stator

$$\alpha_{\text{я}1} = 484\,(1 + 1{,}645 v^{0{,}512}), \qquad 0 \leqslant v \leqslant 15; \qquad (12)$$

for the housing of stator in the zone of end connections of the winding

$$\alpha_{\text{л.ч}} = 600\,(1 + 0{,}717 v^{0{,}522}), \qquad 0 \leqslant v \leqslant 15; \qquad (13)$$

for the pedestal body

$$\alpha_{\text{к.п}} = 890\,(1 + 0{,}706 v), \qquad 0 \leqslant v \leqslant 7, \qquad (14)$$

$$\alpha_{\text{к.в}} = 890\,(1 + 2{,}46 v^{0{,}365}), \qquad 7 \leqslant v \leqslant 15. \qquad (15)$$

Table 2.

(1) Контролируемые элементы электродвигателя	(2) Узлы ЭТС	(3) Нагрев, град		(6) Погрешность расчета	
		(4) Результаты расчета	(5) Опытные данные	(7) град	%
(8) Внешняя поверхность активного железа статора	1	12,28	13,5	—1,22	—9,05
(9) Поверхность раздела между зубцами и ярмом статора	2	20,4	17,85	—2,55	—14,3
(10) Середина зубца пакета статора	3	24,6	21,25	—3,35	—17,75
(11) Внутренняя поверхность расточки статора	4	30,7	—	—	—
(12) Поверхность бочки ротора	5	31,9	—	—	—
(13) Обмотка ротора	6	31,93	—	—	—
(14) Вода внутри паза	7	24,03	21,45	—2,58	—12,7
(15) Пазовая часть обмотки статора	8	28,87	26,52	—2,35	—8,65
(16) Лобовая часть обмотки статора со стороны осевого упорного подшипника	9	28,98	27,12	—1,86	—6,87
(17) Вода внутри двигателя со стороны осевого упорного подшипника	10	22,84	20,5	—2,34	—11,42
(18) Внутренняя поверхность корпуса в зоне пакета статора	11	10,92	—	—	—
(19) Корпус:					
(20) В зоне пакета статора	12	10,38	10,5	—0,12	—1,14
(21) В зоне окололобового пространства обмотки статора со стороны осевого упорного подшипника	13	15,33	14,3	—1,0	—7,0
(22) В зоне осевого упорного подшипника	14	15,82	—	—	—

Key: (1). Controllable/controlled/inspected elements/cells of electric motor. (2). Nodes/units. (3). Heating. deg. (4). Results of calculation. (5). Experimental data. (6). deg. (7). External surface of the active iron of stator. (9). Interface between the teeth and the yoke of stator. (10). Middle of the tooth of the package of stator. (11). Internal surface of the bore of stator. (12). Surface of the barrel/budy of rotor. (13). Rotor winding. (14). Water within the slot/groove. (15). Groove part of the stator winding. (16). End connections of the stator winding from the side of axial thrust bearing. (17). Water within the engine from the side of axial thrust bearing. (18). Internal surface of housing in the zone of the package of stator. (19). Housing. (20). In the zone of the package of stator.

(21). In the zone of the near-frontal space of the stator winding from the side of axial thrust bearing. (22). In the zone of axial thrust bearing.

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The half of the peripheral speed of rotor (for the end connections of winding and housing of stator) is here taken as the determining one. For the heat-transfer coefficients in the zone of step bearing as that being determining half of the peripheral speed of heel (m/s) is undertaken, in this case α they calculate in $W/m^2 \cdot deg$.

Comparison of the results of calculating of temperatures and experimental data (table 2) shows that heating the elements/cells o electric motor interesting can be designed employing the proposed procedure with an accuracy sufficient for the practice. The obtaine results confirm also the legitimacy of the proposed formulas for calculating the parameters of equivalent thermal circuits.

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DETERMINATION OF THE TEMPERATURE OF THE SPOOL OF POWER TRANSFORMERS BY THE METHOD OF MATHEMATICAL SIMULATION.

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The calculation of the temperature field of any spool of transformer is reduced to the solution of the equation of the thermal conductivity of the third kind in question together with the boundary conditions, for assignment of which it is necessary to have available heat-transfer coefficients and temperature of oil at concrete/specific/actual point. However, this calculation is conjugated/combined with the great difficulties, if heat-transfer coefficients are not known.

The proposed method makes it possible to define both the coefficients of heat transfer and temperature field of coil.

Heat distribution in the coil during the flow of its transformer oil according to the vertical and tangential channels (Fig. 1a) occurs not only due to the thermal conductivity, but also as a result of the convective heat exchange. The thermal condition of coil and

oil depends on the character of the processes of heat exchange both within each of these media and between them. These processes individually can be described by differential equations with the appropriate boundary conditions.

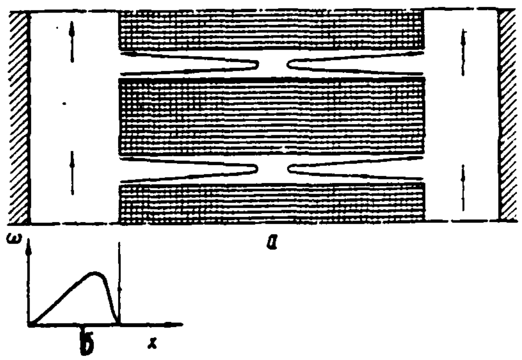

Fig. 1.

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If we assume that the temperature fields of oil and coil are plane-parallel and the thermophysical properties of oil and coil do not depend on temperature, which is possible during the small oscillations of temperature, then differential equations will take the following form:

for oil

$$\lambda_1 \frac{\partial^2 T_м}{\partial x^2} + \lambda_1 \frac{\partial^2 T_м}{\partial y^2} = c_p \rho \left(\omega_x \frac{\partial T}{\partial x} + \omega_y \frac{\partial T}{\partial y} \right), \qquad (1)$$

$$q = -\lambda \frac{\partial T}{\partial n}; \qquad (2)$$

for the coil

$$\lambda_2 \frac{\partial^2 T_к}{\partial x^2} + \lambda_2 \frac{\partial^2 T_к}{\partial y^2} = -p, \qquad (3)$$

$$\alpha (T_к - T_м) = -\lambda_2 \frac{\partial T}{\partial n}, \qquad (4)$$

where ρ - density of oil; λ_1, λ_2 - thermal conductivity respectively

of oil and coil; c_p - heat capacity of oil; ω_x, ω_y - components of rates of motion of oil along the axes x and y; p - density of the losses of the continuous in the coil heat sources; $T_м$, $T_к$ - temperature of oil and coil; q - heat-flux density.

The joint analytical solution of these differential equations is difficult; therefore numerical solution was obtained by the method of successive approximations on the analog unit, which consists of the effective resistance.

The process of heat exchange, described by equation (1), was examined separately for the vertical and tangential channels.

Uptake. During the laminar flow has $\omega_x = 0$; $\omega_y =$ const. Knowing the average speed of the motion of oil in uptake ω_{cp} and utilizing results of work [4], we determine dependence $\omega_y = f(x)$ (Fig. 1b). On the height/altitude of coil we accept $\frac{\partial T}{\partial y} =$ const, with this

$$\frac{\partial T}{\partial y} = \frac{P}{c_p G H}, \tag{5}$$

where P - coil losses; G - consumption of oil, which takes place through the uptakes of winding; H - height/altitude of winding.

Then equation (1) will take the form

$$\lambda_1 \frac{\partial^2 T}{\partial x^2} = C_p \rho \omega_y \frac{\partial T}{\partial y} \tag{6}$$

or in the finite differences

$$\frac{2\lambda_1}{h_1}(T_1 - T_0) + \frac{2\lambda_2}{h_2}(T_2 - T_0) - w(h_1 + h_2) = 0, \quad (7)$$

where $w = c_p \rho \omega_g \frac{\partial T}{\partial y}$; h_1, h_2 - intervals between the points of the spaces, in which the temperature of oil is determined.

Equation (7) was solved on an R-grid on the diagram, represented in Fig. 2. The circuit parameters accordingly [2] are the following:

$$R_1 = R_2 = \cdots = R_i = \frac{h_i m_R}{2\lambda_1};$$

$$R_w = \frac{\varphi_M m_\varphi m_R}{w(h_1 + h_2)}; \quad R_q = \frac{\varphi_M m_\varphi m_R}{q}.$$

where R_1; R_2; R_i - resistances of model, analogous to the thermal resistance of oil; R_w - resistance for the assignment to power of heat generation; R_q - resistance for the assignment of boundary second-order conditions; m_φ - scale of transition from a difference in the temperatures to a potential difference, deg/%; m_R - scale of transition from the thermal ones to the electrical resistance, $\Omega \cdot W/m^2 \cdot deg$; φ_M - supply voltage, %.

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Tangential channel. Process of heat exchange in the tangential channel somewhat more complicated than in the vertical. Besides the motion of oil along the axis of channel as a result of free convection from the lower coil to the middle of channel appears the transverse motion of oil. Transverse convective heat transfer is

taken into consideration by the introduction of the equivalent coefficient of thermal conductivity. Therefore for the tangential channel, just as for the vertical, was examined one-dimensional problem. Then equation (1) in the finite differences took the form

$$\frac{2\lambda_{экв}}{h_1}(T_1 - T_0) + \frac{2\lambda_{экв}}{h_2}(T_2 - T_0) - w(h_1 + h_2) = 0. \qquad (8)$$

Here $\lambda_{экв}$ - equivalent thermal conductivity of oil, determined through the Prandtl numbers and Grashof [3], $\lambda_{экв} = \lambda\varepsilon$, where $\varepsilon = 0{,}105\ (G_rP_r)^{0,3}$.

The speed of the motion of oil in the tangential channel was accepted by an order less than in the vertical. The temperature differential of oil on half of tangential channel was determined from following formula [5]:

$$\Delta T = \frac{r\sqrt{q}}{31{,}0s}, \qquad (9)$$

where r - radial size/dimension of coil; s - height/altitude of tangential channel.

Equation (8) was solved on an R-grid on the diagram, given in Fig. 3.

As a result of solving equations (7) and (8) is obtained the temperature differential between surface of coil and oil $(T_к - T_м)$, which was used for determining the coefficient of the heat transfer

$$\alpha = \frac{q}{T_к - T_м}. \qquad (10)$$

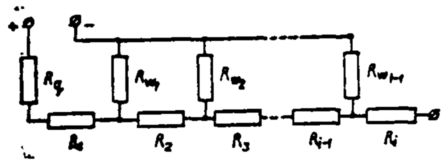
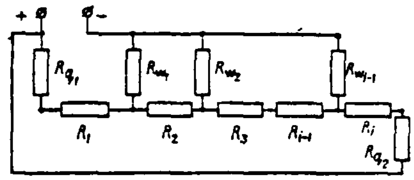


Fig. 2.



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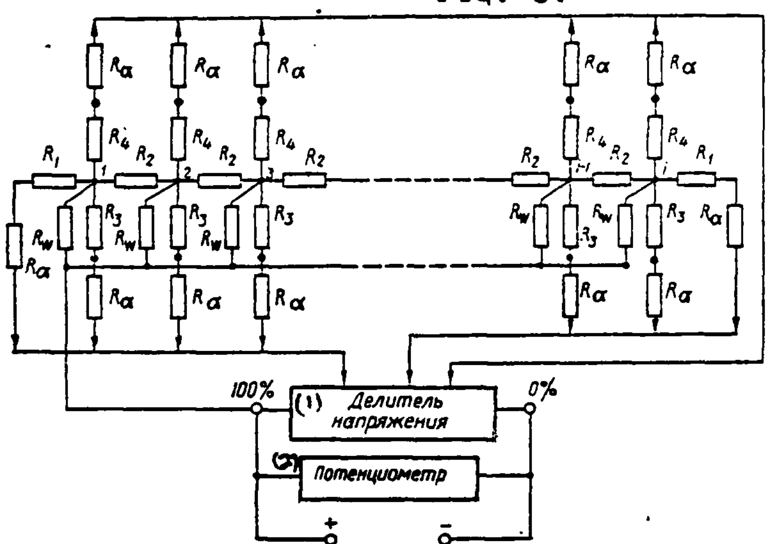

Fig. 4. Key: (1). Voltage divider. (2). Potentiometer.

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For solving equation (3) the diagram, represented in Fig. 4, was utilized, where resistances R_1, R_2, R_3 and R_4 present on the model the thermal resistance of copper and insulation/isolation; R_α - resistance of heat emission on the boundary of turn and oil; R_w - resistance, with the help of which on the model the power of internal heat sources is assigned;

$$R_1 = R'_м + R'_{из},$$

where $R'_{\text{м}} = \frac{a}{\lambda_{\text{м}} b} m_R$; $R'_{\text{из}} = \frac{(a' - a)}{2\lambda_{\text{из}} b'} m_R$; $\frac{a \times b}{a' \times b'}$ - sizes/dimensions of rectangular skinned wire and in insulation/isolation; $R_2 = 2R_1$; $R_3 = R_4 = R''_{\text{м}} + R''_{\text{из}}$; $R''_{\text{м}} = \frac{b}{\lambda_{\text{м}} a} m_R$; $R''_{\text{из}} = \frac{b' - b}{2\lambda_{\text{из}} a'} m_R$; $R''_{\alpha} = \frac{m_R}{\alpha a'}$; $R'_{\alpha} = \frac{m_R}{\alpha b'}$. .

As a result of solving equation (3) is obtained the temperature of each turn of coil, also, on its surface, which makes it possible to determine the temperature field of oil. the obtained temperature of oil and coil is approximate, since it is approximately determined ∂T/∂x and ∂T/∂y according to empirical formulas (5) and (9). However, this temperature - is the initial one for the repeated solution of equations (3) (7) and (8).

Fig. 5 compares the results of simulation (curve II) after the second approximation/approach with the results of the experimental investigation of the model of the winding of transformer (curve I). According to the experimental data maximum temperature is located nearer to the internal uptake. This is explained by the fact that in the internal duct under the transitions between the coils the packing, which partially close the access of oil into the tangential channels, are established/installed. This condition was not considered during the simulation; therefore the obtained curve was symmetrical relative to the vertical axis of coil. However, in spite of this, from Fig. 5 it is evident that the results with a sufficient degree of accuracy can be obtained for two approximations/approaches.

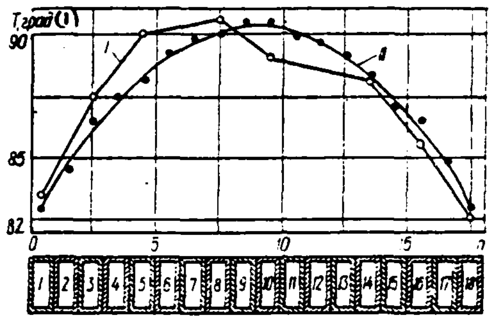

Fig. 5. Key: (1). deg.

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THE PROCEDURE OF CALCULATION OF AN ACTIVE TYPE COMPENSATED LINEAR INDUCTION MACHINE.

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In active type linear induction machines into the electrical energy is converted kinetic energy of the flow of the liquid metal, which moves to channel with the variable cross-sectional area. Three cases of changing the cross-sectional area of the channel are possible: 1) width remains constant/invariable, and height/altitude grows/rises; 2) and height/altitude, and width simultaneously they change along the length; 3) at the constant/invariable height/altitude width grows/rises. The modes/conditions of the work of machine with the constant or variable/alternating/variable slip of liquid metal relative to the traveling wave of magnetic field are possible.

The procedure of calculation of the idealized model of linear machine in the mode/conditions with the constant slip during the

motion of liquid metal in the channel with the expanding walls is described below. The height/altitude of channel is constant. It is assumed that the effect of the longitudinal edge effect of the primary circuit is completely compensated with the help of auxiliary coils, whose currents are distributed over the surface of the interfaces of active region/core with the end sections. The longitudinal edge effect of secondary circuit is not considered. It is proposed also that the lateral busbars/tires of channel are prepared from the material with the infinite electrical conductivity. The currents of the primary winding which creates the traveling wave of linear current load with the constant amplitude and the variable/alternating/variable phase speed, are distributed on entire clearance by height/altitude $\delta' = k_\delta k_u \delta$. Coefficients k_δ, k_u consider the effect of the serration of inductor [1]. It is considered that working the body is selected and its parameters are known: temperature T, electrical conductivity σ, density ρ and the coefficient of dynamic viscosity

The proposed methodology is intended for the check computation of linear induction machine with variable speed of field and liquid metal. In it the results of theoretical studies, published in works [2, 5, 9] are used.

From the preliminary thermodynamic calculation of thermal cy-

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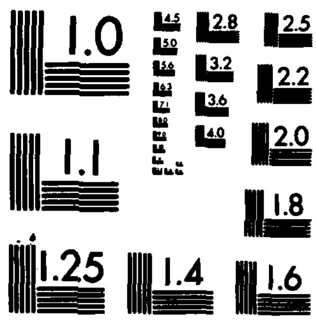

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they are known the liquid-metal flow rate per second through the cross section of channel, and also the velocity at the inlet u_1 and at the outlet u_2 from the channel. The speed of liquid metal in the active region/core of channel is determined from the equation of continuity for an incompressible fluid at the known inlet velocity

$$u(x)=\frac{u_1}{1+\varepsilon x}, \qquad (1)$$

where $x=x_1/l$ - dimensionless independent variable ($0\leq x\leq 1$), l - length of machine; $\varepsilon=\varepsilon_0 l$ - dimensionless low parameter, determined from the known inlet velocities and at the output/yield,

$$\varepsilon=\frac{u_1}{u_2}-1. \qquad (2)$$

Phase wave velocity of magnetic field is determined from the condition of the constancy of slip s:

$$v(x)=\frac{v_1}{1+\varepsilon x}. \qquad (3)$$

The phase of wave $\psi(x)$ is found by integration from expression $v(x)=\omega(dx/d\psi)$:

$$\psi(x)=\alpha(x+0.5\varepsilon x^2), \qquad (4)$$

where $\alpha=\alpha_0 l$ - dimensionless phase factor for the case of constant phase wave velocity of field. Pole pitch of machine changes along the length according to the law

$$\tau(x)=\frac{\tau_0}{1+\varepsilon x}. \qquad (5)$$

Here $\tau_0=\frac{\pi v_1}{\omega}=\frac{\pi}{\alpha_0}$ - pole pitch of machine at the constant phase speed.

Width b_1 and height/altitude Δ of channel are chosen from the condition of small hydraulic wall-friction loss of channel. The

optimum relationship/ratio of width and height/altitude with the minimum of hydraulic losses and the maximum factor of power cos φ is located in the number domain $k=(b_1/\Delta)=3-4$.

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Choosing relationship/ratio k over the known cross section at entrance $F_1=G/\rho u_1$, we determine the height/altitude of the channel

$$\Delta=\sqrt{\frac{F_1}{k}}, \tag{6}$$

in this case width it changes according to the linear law:

$$b=b_1(1+ax). \tag{7}$$

Desirable also that the height/altitude of clearance would not exceed third of pole pitch. The wall thickness of channel is calculated from the required mechanical strength with the given one of pressure in the channel. The thickness of thermal insulation is chosen from the calculation of the minimum heat losses to the walls.

The length of machine preliminarily is determined from the condition that the conducted/supplied primary power P_1 is expended/consumed on covering of hydraulic power losses to friction against the walls of channel and to electromagnetic power $P_{эм}$, generated in the channel of the machine:

$$l=\frac{P_1}{P'_{эм}+p'_{тр}}; \tag{8}$$

then it is more precisely formulated according to the condition of

packing code at the length of the inductor of the integer of wavelengths ($\psi(1)=2\pi p$)

$$l = \frac{2\pi p}{\alpha_0(1+0{,}5\varepsilon)}. \quad (9)$$

It is here accepted

$$P_1 = 0{,}5G(u_1^2 - u_2^2), \quad (10)$$

$$P_{эм} = lP'_{эм} = lP'_{эм0}\left\{1 + \varepsilon\left[-0{,}5 + \frac{2}{1+R_m^2} + D\right]\right\}, \quad (11)$$

$$p_{тр} = lp'_{тр} = l\frac{\rho\lambda b_1 u_1^3}{4(1+\varepsilon)}\left[1 + \frac{\Delta(2+\varepsilon)}{b_1(1+\varepsilon)}\right], \quad (12)$$

where

$$D = \frac{3s - 6R_m^2(1+s) + R_m^4(2-s)}{\alpha s R_m(1+R_m^2)^2}; \quad (13)$$

$$P'_{эм0} = \frac{4\mu\omega b_1 k_{об}^2 A_л^2}{\delta'\alpha_0^2}\,\frac{R_m}{1+R_m^2}; \quad (14)$$

R_m - magnetic Reynolds number,

$$R_m = \frac{2\pi f\mu\sigma s}{\alpha_0^2}; \quad (15)$$

λ - coefficient of friction of liquid metal against the walls of channel. Remaining designations are conventional.

For the purpose simplicities of the recording of formula for the integral relationships/ratios of machine are given for the low values of ε. Linear current load is determined by the assigned amplitude of induction B_Δ in the center of the clearance:

$$A_л = \frac{\alpha_0\delta' B_\Delta}{2\sqrt{2}\mu\eta_m k_{об}}, \quad (16)$$

where η_m - modulus/module of the expression

$$\eta = -\frac{j}{1+jR_m} + \varepsilon\frac{s - j(2+s)R_m}{\alpha s(1+jR_m)^3}. \quad (17)$$

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For calculating the three-phase winding, which creates in the clearance the wave of magnetic field with the variable/alternating/variable phase speed, the methods, used during the construction of the usual windings of linear machines with the constant velocity of field, they are unsuitable. In work [8] is in detail presented the method of engineering an m-phase winding for case of q=1 under the law of induction change assigned in general form in the clearance. Are given conditions for calculating the length of current zones in the case of constant phase displacement between the adjacent current zones, conditions are derived/concluded, with which the current and voltage in the phases of winding are symmetrical. One of the methods of engineering the single-phase winding with variable/alternating/variable phase wave velocity of field is presented in works [3, 4, 9].

Let us consider a special case of engineering the three-phase winding of inductor with the constant amplitude of linear current load. Spools are wound around the yoke and are fed by the balanced system of currents. The amplitude of phase currents preliminarily can be computed according to the usual formula

$$I = \frac{p\tau_y A_n}{\sqrt{2} m k_{o6} w_{\Phi}}, \quad (18)$$

where

$$w_\phi = \frac{U_л}{4\sqrt{6} f k_{об} \tau_0 B_\Delta}. \tag{19}$$

At variable/alternating/variable phase wave velocity of magnetic field (3) pole pitch (5) and toothlike space of machine change along the length:

$$t_z(x) = \frac{\tau_0}{mq} \frac{1}{1+\varepsilon x}, \tag{20}$$

where q=2 - number of pole slots and phase; m=3 - number of phases.

From the condition of the constancy of the amplitude of linear current load at the length of each current zone, equal to toothlike space,

$$A_x = \frac{Iw}{t_z(x)}, \tag{21}$$

let us find the law of a change in the number of turns along the inductor:

$$w(x) = \frac{A_x \tau_0}{Imq} \frac{1}{1+\varepsilon x}. \tag{22}$$

Let in the real inductor the currents of winding be discrete/digital currents. It is necessary to determine the coordinates of beginning and end of the current zones. With q≠1 it is possible to utilize either a condition of the equality of the lengths of current zones ($t_z = \mathrm{const}$) in each phase band or a condition of the constancy of phase displacement ($\Delta\psi$=const) of adjacent current zones [10, 8].

Let us decompose the length of inductor on 2pm phase bands on 60

electrical degrees in each. According to the known law of a change in phase (4) from the condition

$$\cos\psi(x_k) = \cos\frac{2\pi k}{2pm} \qquad (23)$$

in the formula

$$x_k = \frac{1}{\varepsilon}\left[-1 + \sqrt{1 + \frac{2\varepsilon k\pi}{m\alpha}}\right], \qquad k = 0, 1, 2, \ldots, 2pm \qquad (24)$$

the coordinate of the ends of each phase band is located. With q=2 the missing coordinate within the phase band can be determined, if one assumes that the magnetic flux of each phase band is distributed equally between the current zones. From this condition from the formula

$$x_n = \frac{1}{\varepsilon}\left[-1 + \sqrt{1 + \varepsilon(x_{n-1} + x_{n+1}) + 0{,}5\varepsilon^2(x_{n-1}^2 + x_{n+1}^2)}\right] \qquad (25)$$

let us find the missing coordinate. Here x_{n-1}, x_{n+1} - beginning and the end of each phase band; n takes values of n=1, 3, 5, ... (Z-1), where Z=2pmq - number of teeth.

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After substituting the length of each current zone (toothlike space)

$$l_{zr} = x_r - x_{r-1} \qquad (26)$$

into expression (22), let us find the number of turns in each current zone, which corresponds to one spool:

$$w_r = \frac{A_z}{I} l_{zr}. \qquad (27)$$

Total number of turns of the winding of one inductor

$$w_{\Sigma} = \sum_{r=1}^{z} w_r \qquad (28)$$

The sizes/dimensions of tooth, slot/groove and yoke of magnetic circuit are calculated from the usual formulas of electrical machines [7]. The effective resistance of the winding of the inductor

$$r_1 = \frac{w_\Sigma l_w}{\sigma_1 q_1}, \qquad (29)$$

where l_w - average/mean length of the turn (it is calculated after the determination of the geometric dimensions of inductor); σ_1, q_1 - conductivity and the section of copper conductor. The calculation of induced drag of scattering the spools, wound around the yoke, requires supplementary special investigations. However, resistance of scattering approximately can be taken into account by certain coefficient of scattering during the calculation of induced drag of the phase:

$$x_{\text{ин}} = (1+\sigma_s)\, 2\pi f L_{\text{ср}} = \\ = (1+\sigma_s)\, 2\pi f p q \frac{\mu b_1 l_z}{\delta'} \left[\frac{1}{3}(11q^2+1) - 12pq^2 \frac{t_z}{l} \right], \qquad (30)$$

where σ_s - coefficient of scattering; $L_{\text{ср}}$ - average/mean equivalent phase inductance in the mode/conditions with the balanced system of currents [11].

Amplitude and phase of the compensating currents is determined from the expressions

$$I_{k1} = \frac{4k_{o6}A_x}{\alpha_0(1+jR_m)} \left[R_m \frac{1-s}{2s} \left(1 + \sqrt{1 + j\frac{4s}{R_m(1-s)^2}} \right) + j \right], \qquad (31)$$

$$I_{k2} = \frac{4k_{o6}A_x}{\alpha_0(1+jR_m)} \left[R_m \frac{1-s}{2s(1+s)} \left(-1 + \sqrt{1 + j\frac{4s(1+s)^2}{R_m(1-s)^2}} \right) - j \right] e^{-j\alpha}. \qquad (32)$$

Indices 1 and 2 designate beginning and end of the inductor respectively.

A number of turns of one bucking coil is found from the condition of the equality of magnetizing force of bucking coil and magnetizing force of winding [1]:

$$w_{k1,2}=\frac{w_{\Sigma}k_{\text{об}}I}{2\pi pI_{k1,2}}. \tag{33}$$

Mechanical $P_{\text{мх}}$, complete (apparent) S, reactive/jet Q powers and electromagnetic force $F_{\text{эм}}$, which acts on the liquid metal, are determined from the formulas

$$P_{\text{мх}}=(1-s)P'_{\text{эм0}}l\left\{1-\varepsilon\left[-0{,}5+\frac{2(-1+\alpha+\alpha R_m)}{\alpha s(1+R_m^2)^2}+D\right]\right\}, \tag{34}$$

$$Q=\frac{P'_{\text{эм0}}l}{R_m}\left\{1-\varepsilon\left[-0{,}5+\frac{1-R_m^2}{1+R_m^2}-\frac{2R_m(1+4s-3R_m^2)}{\alpha s(1+R_m^2)^2}\right]\right\}, \tag{35}$$

$$S=\sqrt{P_{\text{эм}}^2+Q^2}, \tag{36}$$

$$F_{\text{эм}}=F_{\text{эм0}}\left\{1-\varepsilon\left[-1+\frac{2}{1+R_m^2}\left(1-\frac{1-R_m^2}{\alpha R_m}\right)+D\right]\right\}, \tag{37}$$

where

$$F_{\text{эм0}}=\frac{4\mu b_1 lk_{\text{об}}^2A_n^2}{\delta'\alpha_\varphi}\frac{R_m}{1+R_m^2}. \tag{38}$$

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Electrical efficiency of the machine

$$\eta_{\text{эл}}=1-\frac{p_{\Sigma\text{эл}}}{P_1}, \tag{39}$$

where

$$p_{\Sigma\text{эл}}=p_{\text{эл2}}+p_{\text{ст}}+p_{\text{эл1}}+p_{\text{экр}}+p_{\text{Fe}}. \tag{40}$$

First term in expression (40) indicates electrical losses in the liquid metal

$$p_{эм2} = P_{эм} - P_{мх}, \qquad (41)$$

the second - loss in the conducting walls of channel [2],

$$p_{ст} = \left[\frac{B_{\Delta}(u_1 + u_2)}{2(1-s)}\right]^2 \sigma_{ст}\Delta_2 l b_1, \qquad (42)$$

where $\sigma_{ст}$ and Δ_2 - conductivity and wall thickness. Electrical losses in primary winding $p_{эл1}$, losses in bucking coils $p_{эл\,kk}$ and in the iron of inductor p_{Fe} are calculated from the usual formulas of electrical machines [7].

Complete efficiency taking into account the hydraulic losses

$$\eta = 1 - \frac{p_{\Sigma эм} + p_{тр} + p_{p}}{P_1}, \qquad (43)$$

where the hydraulic duct losses due to the expanding geometry are computed according to following empirical formula [6]:

$$p_p = \xi\rho\Delta b_1 \frac{u_1^3}{2} \sin\Theta. \qquad (44)$$

Power factor can be counted in the formula

$$\cos\varphi = \frac{P_{эм}}{S}. \qquad (45)$$

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